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PART II

A STUDY OF CONVENTIONAL AIRPLANE HANDLING QUALITIES REQUIREMENTS

PART II. LATERAL-DIRECTIONAL OSCILLATORY HANDLING QUALITIES

I. L. ASHKENAS

SYSTEMS TECHNOLOGY, INC.

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I. L. ASHKENAS

FOREWORD

This report represents a portion of the effort devoted under Contract No. AF 33(657)-10407 to the codification of conventional airplane handling qualities requirements. The work was performed by Systems Technology, Inc., Hawthorne, California, under Project No. 8219, Task No. 821905, sponsored by Air Force Flight Dynamics Laboratory of the Research and Technology Division. The research period was from January 1963 through May 1965, and the manuscript was released by the author in June 1965 as STI-TR-133-1. The RTD project engineers have been R. J. Wasicko, P. E. Pietrzak and Lt. J. R. Pruner.

It was originally expected that the efforts reported here would be incorporated into a fairly definitive design guide. To this end, a draft version of the report dated 18 June 1964 was circulated to various specialists in the field to obtain their reaction and comment. The notion of the design guide was later abandoned as being somewhat premature; but the comments received were given careful consideration in the present final report. These comments are abstracted in the Appendix, and the author gratefully acknowledges the helpful suggestions, ideas, and experiences contributed by the groups and individuals represented therein.

This technical report has been reviewed and is approved.

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ABSTRACT

This report is a codification in two parts of conventional aircraft handling qualities criteria. The results of this effort are to serve as an intermediate design guide in the areas of lateral-directional oscillatory and roll control. All available data applicable to these problem areas were considered in developing the recommended new criteria. Working papers were sent to knowledgeable individuals in industry and research agencies for comments and suggestions, and these were incorporated in the final version of this report. The roll handling qualities portion of this report uses as a point of departure the concept that control of bank angle is the primary piloting task in maintaining or changing heading. Regulation of the bank angle to maintain heading is a closed-loop tracking task in which the pilot applies aileron control as a function of observed bank angle error. For large heading changes, the steady-state bank angle consistent with available or desired load factor is attained in an open-loop fashion; it is then regulated in a closed-loop fashion throughout the remainder of the turn. For the transient entry and exit from the turn, the pilot is not concerned with bank angle per se, but rather with attaining a mentally commanded bank angle with tolerable accuracy in a reasonable time, and with an easily learned and comfortable program of aileron movements. In the lateral oscillatory portion of this effort, in defining requirements for satisfactory Dutch roll characteristics, a fundamental consideration is the fact that the motions characterizing this mode are ordinarily not the pilot's chief objective. That is, he is not deliberately inducing Dutch roll motions in the sense that he induces rolling and longitudinal short-period motions. Dutch roll oscillations are side products of his attempts to control the airplane in some other mode of response, and they are in the nature of nuisance effects which should be reduced to an acceptable level. In spite of its distinction as a side effect, adequate control of Dutch roll is a persistent handling qualities research area and a difficult practical design requirement. The difficulties stem from the many maneuver and control situations which can excite the Dutch roll, and from its inherently low damping. Since any excitation of the Dutch roll is undesirable, the effects of disturbance inputs are almost uniformly degrading to pilot opinion rating. Nevertheless, removal of such influence does not eliminate the need for some basic level of damping. A worthwhile approach to establishment of Dutch roll damping requirements is to first establish the basic level, and then to study the varied influences of the disturbance parameters. This approach provides the basis for the material contained in this report.

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TABLE

ILLUSTRATIONS

TABLE

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SYMBOLS

a_y	Acceleration along y axis, positive to right
A	Body (principal) axis amplitude ratio of angular rolling acceleration to yaw angle
b	Wing span
$C_{1/2}$	Number of cycles to damp to one-half amplitude
db	Decibels
g	Acceleration due to gravity
G	Constant
I_{xz}	Product of inertia about xz axes
I_x, I_y, I_z	Moments of inertia about x, y, z axes, respectively
L	Rolling acceleration due to externally applied torque
L_i	Variation of L with input or motion quantity particularized by subscript
L_i'	$\dfrac{L_i + (I_{xz}/I_x)N_i}{1 - (I_{xz}^2/I_x I_z)}$
N	Yawing acceleration due to externally applied torque
N_i	Variation of N with input or motion quantity particularized by subscript
N_i'	$\dfrac{N_i + L_i(I_{xz}/I_z)}{1 - (I_{xz}^2/I_x I_z)}$
p	Rolling angular velocity about x axis, positive right wing down
p_o	Steady roll rate
R	Pilot rating number
s	Laplace transform, $s = \sigma + j\omega$
T	General first-order time constant

T_{φ_1}, T_{φ_2}	Aileron roll numerator time constants for $\omega_{\varphi}^2 < 0$
$T_{1/2}$	Time in seconds to damp to one-half amplitude
T_R	Roll subsidence time constant
T_s	Spiral mode time constant
U_o	Linear steady-state velocity along x axis
v	Side velocity, positive to right
v_e	"Indicated" side velocity, $v_e = \sqrt{\rho/\rho_o}\, U_o\beta$
y	Lateral stability axis, positive out right wing
Y_v	Variation of side acceleration with side velocity
$Y^*_{\delta_r}U_o$	Variation of side acceleration with rudder deflection
β	Sideslip angle, $\beta = v/U_o$
δ	Control angular deflection
δ_a	Aileron angular deflection
δ_r	Rudder angular deflection
κ	Root locus gain constant; high frequency gain
$\kappa_{\dot{\varphi}}$	κ for roll rate to aileron transfer function
ζ	Damping ratio of linear second-order system particularized by the subscript
ζ_d	Damping ratio of Dutch roll second-order
ζ_{sp}	Damping ratio of longitudinal short-period mode
$\zeta\omega$	Damping
θ	Pitch angle
σ_i	RMS value particularized by the subscript
φ	Roll angle, positive right wing down
Φ_{v_g}	Random side gust spectral form
ψ	Heading angular displacement
ω	Undamped natural frequency of a second-order mode particularized by the subscript (rad/sec)

Subscripts

a	Aileron
b	Body-fixed principal axes
c	Controlled element, or crossover
d	Dutch roll
g	Gust
p	Roll rate, or pilot
r	Rudder, or yaw rate
R	Roll subsidence
s	Spiral divergence
sp	Short period
v	Side velocity
β	Sideslip
δ	Control deflection particularized by the subscript
φ	Roll transfer function

SECTION I

BACKGROUND

In attacking the requirements for satisfactory oscillatory (Dutch roll) characteristics, a fundamental consideration is the fact that the motions characterizing this mode are, for ordinary flying, not the pilot's chief concern. That is, he is not ordinarily deliberately inducing Dutch roll motions in the sense that he does deliberately induce roll-subsidence and longitudinal short-period motions. Rather, Dutch roll oscillations are side products of his attempts to control the airplane in some other mode of response and, as such, they are in the nature of nuisance effects which should be reduced to an acceptable level. If the Dutch roll is not excited by normal maneuvers, then its nuisance value is inherently low, as is its required (or desired) damping, ζ_d. Under such circumstances a "good" $\zeta_d \doteq 0.15$ is considerably lower than a "good" $\zeta_{sp} \doteq 0.7$. This spread is indicative of the basic difference between a primary mode of control and a secondary side effect.

In spite of its distinction as a secondary effect, adequate control of Dutch roll motions is a persistent handling qualities research area and a difficult practical design requirement. The difficulties stem from the many maneuver or control situations which can excite this mode and from its inherently low natural damping. Table I is a summary of "Lateral Control and Response Considerations" pertinent to the problem area. It describes and quantizes a large number of possible situations in which lateral-directional interactions can occur. To some extent the situations considered were selected because of the possibility of reducing their implications to the relatively simple literal forms shown. Other situations, not so easily definable, may in fact be more representative of actual piloting problems. The general importance of each situation listed is surely doubtful, but as a check list the table serves to show that there are many differing effects which can contribute to handling qualities problems

connected with the Dutch roll mode. In fact the discussions given in the last column indicate that a large number of the problems associated with the list have already occurred in flight or fixed-base simulation. To some extent this is a natural consequence of the literature search, discussions, etc., that preceded the derivation of the list itself.

A quick perusal of the approximate literal expressions given in Table I shows the recurring predominance of the cross-coupling terms,

$$\frac{L'_\beta}{N'_\beta}\text{, associated also with } \left|\frac{\varphi}{\beta}\right|_d \text{ or } \left|\frac{\varphi}{v}\right|_d \text{ and } \frac{\omega_\varphi^2}{\omega_d^2}$$

$$\frac{N'_{\delta_a}}{L'_{\delta_a}}\text{, associated also with } \frac{\omega_\varphi^2}{\omega_d^2}$$

and in some cases (notably Item 7) the appearance of the terms

$$N'_p - \frac{g}{U_o}\,, \quad \frac{L'_{\delta_r}}{N'_{\delta_r}}$$

The importance of L'_β/N'_β as a Dutch roll disturbance parameter has long been recognized,[1-4] but its distinct contribution in differing situations has not received widespread consideration. Thus, recent handling qualities correlations relating pilot opinion to variations in Dutch roll characteristics usually <u>assume</u> that the correct coupling parameter related to L'_β/N'_β is either $|\varphi/\beta|_d$ or $|\varphi/v_e|_d$. This may or may not be the case, depending on the tasks given the pilot and the particular task or response which influenced his opinion most. The fact that both the above, and other, forms of the L'_β/N'_β effect appear in Table I is indicative of potential errors in the indiscriminate application of such correlations to differing situations.

A similar comment applies to correlations made with respect to $N'_{\delta_a}/L'_{\delta_a}$ effects, the current vogue (to some extent fostered by the author[6]) being to correlate opinion data with respect to the parameter $(\omega_\varphi/\omega_d)$.[7-9,15,27] This practice is, however, not so well ingrained as is the use of $|\varphi/v_e|_d$, and there are already stirrings of rebellion[8,11,42] in the ranks.

The secondary parameters, $[N'_p - (g/U_o)]$ and $L'_{\delta_r}/N'_{\delta_r}$, have received little formal recognition in handling qualities experiments. However, the ability to make aileron-only turns is strongly influenced by the former, which has been carefully considered in setting up a number of "good" stability augmentation systems. Such considerations, invariably involving additional feedbacks to the rudder (e.g., p or "shaped" δ_a), also require attention to the value of $L'_{\delta_r}/N'_{\delta_r}$. The latter is of course of direct importance in deliberate sideslips, which, for the decrab maneuver, involve implications additional[16] to those listed in Table I. It appears, generally speaking, that the secondary parameters may be of primary importance for high lift flight associated with low speed approach and landing situations, but will probably not be of major significance for climb, cruise, or high speed.

For the latter "normal" flight conditions, it seems that the basic disturbance parameters are indeed associated with those already in use. However, the most suitable specific and/or general forms of the parameters have not yet been adequately scrutinized. Since both φ/v_e-like and ω_φ/ω_d-like effects provide undesirable excitation of the Dutch roll mode, their gross effects are almost uniformly degrading to pilot opinion rating. Nevertheless, removal of such influences does not eliminate the requirement for some basic level of damping. It appears, therefore, that a worthwhile approach to Dutch roll damping requirements is to first establish the basic level and then to study the varied influences of the disturbance parameters. This approach, which to some extent has already been attempted,[28] is the basis for the discussions and presentations to follow.

SECTION II

BASIC DAMPING REQUIREMENTS

In considering the basic damping requirement we must search for pilot opinion data which are largely uncontaminated by either "ω_φ/ω_d" or "$|\varphi/v_e|_d$" effects. Furthermore, because the Dutch roll motions in such circumstances are predominantly yawing and sideslipping, the suitability of fixed-base simulator results seems somewhat questionable. Accordingly, the only available data considered pertinent to the basic damping requirement (without reservation) are those obtained in flight for "low" values of φ/v_e or φ/β and for known low values of $N'_{\delta_a}/L'_{\delta_a}$. There are three primary sources of data which fit this description, NASA,[3,8] McDonnell,[4] and CAL[7,9] variable-stability-airplane flight test results.

Figure 1 presents selected NASA data for the conditions listed. In addition to the "conventional" $|\varphi/\beta|$, $|\varphi/v_e|$ (in deg-sec/ft) parameters, the pertinent ranges of $\omega_d^2|\varphi/\beta|$ are also shown. It may be appreciated from Table I, Item 3, that this "new" parameter measures the rolling acceleration-to-sideslip ratio of the Dutch roll motions following a side-gust step input or release from a steady sideslip (more about this later). The values of $N'_{\delta_a}/L'_{\delta_a}$ used in the Ref. 3 tests were adjusted by the pilot to be "optimum" and were presumably close to zero. In fact, however, the complete faired data of Ref. 8 (not presented) show a slight difference in ratings between $N_{\delta_a} = 0$ and N_{δ_a} for best opinion. Nevertheless it can be assumed that the majority of the data shown are free of significant $N'_{\delta_a}/L'_{\delta_a}$ (or ω_φ/ω_d) interactions. This is further verified by the fact that in most cases the over-all rating* differs by less than half a point from the rating of the

*Over-all ratings were delivered "...on the basis of lateral oscillatory characteristics (pilot controls fixed), and lateral-directional handling qualities in both smooth and simulated rough air, ..."

lateral oscillatory characteristics alone. Differences of one rating point or more are indicated by the flagged symbols — and these have been given predominance over the corresponding over-all ratings in the fairings shown. The basis for this is the notion that the controls-fixed oscillatory ratings can in no way be influenced by (unknown) control surface derivatives and are therefore the closest possible approach to the basic relationship desired here. In further accord with this desire, the data points selected were limited to ranges of the φ/β-related parameters, which were as low as possible but still compatible with retaining sufficient data to establish meaningful trends. (The remaining, higher φ/β points will be considered later.)

As to the data themselves, Fig. 1a shows significant differences in rating level among the various pilots participating in the Ref. 3 tests; but the trends are gratifyingly consistent (except for Pilot B, whose three points are not self-consistent and are therefore not faired). The cross-hatched median line, which lies roughly half way between the extreme rating curves, could be considered conservative on the basis that there are more pilots below it than there are above it. Pilot A of Ref. 8 (presumably no relation to Pilot A of Ref. 3) falls reasonably close to the median line. In contrast, the data of Fig. 1b show no consistent differences among the Ref. 3 pilots, and the single faired line on each plot is reasonably representative of all pilots.

The data shown in Fig. 2, again selected for reasonable "low" ranges of the φ/β-related parameters, represent a single pilot's ratings of only the lateral oscillatory characteristics (this was the only "task" performed in the Ref. 4 flight tests). In line with the notions outlined above, such data are considered to be uncontaminated by N'_{δ_a} effects and thus qualify to establish the basic requirements sought here. The parameter "A" is the "body (principal) axis amplitude ratio of angular rolling acceleration to yaw angle" and is closely related to $\omega_d^2|\varphi/\beta|$; it, rather than φ/β or φ/v_e, is the parameter chosen in Ref. 4 to correlate φ/β-related effects, as will be fully discussed in the next section. In the meantime it is pertinent to note that there is, indeed, a fairly sizable separation

of the data as a function of the range of "A" for what would ordinarily be considered a rather insensitive region in $|\varphi/v_e|$ or $|\varphi/\beta|$. The fairings shown acknowledge this separation and in the main correspond to minimum ratings (i.e., the lower range of "A") for the indicated ranges of ω_d. The one exception is the fairing shown in Fig. 2a for the $2.27 < \omega_d < 3.13$ data corresponding to the higher "A" range, because this represents the more complete set.

The Fig. 3 data were obtained for a fairly comprehensive series of handling qualities tasks, and are backed up by pilots' comments and fairly complete sets of "effective" stability derivatives. Using the latter, it was possible to select flight test data representative of "good" basic roll control,[35] and of low $N'_{\delta_a}/L'_{\delta_a}$ effects; and to segregate these further into the "low" φ/β sets shown. Unfortunately, most of the applicable Ref. 7 data are for relatively high dampings, which have little effect on pilot rating. However the Ref. 9 data do cover the more interesting low damping region. In each of the test series a single pilot rated all configurations.

Figure 4 presents all of the faired data of Figs. 1–3 in direct superposition. Careful comparisons of the curves in Fig. 4 show that for comparable conditions the ratings given in the CAL tests[7,9] are, on the average, low by about one point.* For example, the curve labeled 4 is low with respect to both curves 1 and 3 when either of the variables $(\zeta\omega)_d$ or ζ_d (Figs. 4a and b, respectively) are considered. Curve 5 is low with respect to 1 on the $\zeta\omega$ plot, but falls into line on the ζ plot. Curve 6 compared to curves 1, 3, and 8, and curve 7 compared to curve 10, are both low on the basis of either Fig. 4a or 4b. These differences may be due to the normal variability between pilots (e.g., see Fig. 1) and the fact that only one pilot was involved in each of these sets of results; differences in the missions envisioned (Ref. 7 simulated entry, Ref. 9 landing approach); or possibly to the different descriptions used to identify the numerical ratings. This last "explanation" cannot be seriously considered without casting some doubt on all the cross-comparisons of Fig. 4, since the sets of descriptions were different for each of the

*This also shows up in Fig. 13a.

investigating groups involved; nevertheless in all cases ratings of 3.5 and 6.5 were considered the boundaries between satisfactory and unsatisfactory, and between unsatisfactory and unacceptable (or tolerable and intolerable[4]), respectively. As further evidence of roughly a one-point deficiency in the Ref. 9 ratings (and of direct interest in itself), Fig. 5 compares the Ref. 9 curve of Fig. 3, raised one point, with miscellaneous single data points culled from the various sources indicated. All these data are for conditions corresponding to landing approach. In those cases where numerical ratings were not given (flagged symbols) the writer assigned a number based on the recorded pilots' comments. Also, one case (C-130B) is undoubtedly influenced by the very poor heading control reported and is therefore represented by a filled symbol; it is included to help establish trends for the very low frequency regime represented by the assembled points. It may be seen that the raised Ref. 9 fairing fits the individual points fairly well when plotted versus $(\zeta\omega)_d$, but is grossly inadequate when plotted versus ζ_d.

Figure 6 is a revised version of Fig. 4 with the lines labeled 4 through 7 raised one point, as discussed above; and the lines labeled 1, 2, 3, 8, and 9 lumped into a single cross-hatched region. The cross-hatched region corresponds to selected data obtained for $1.57 < \omega_d < 3.59$. The remaining data in roughly the same range, curves 4, 5, and 6, fall more nearly into over-all line with the level and trend of the cross-hatched region when plotted versus $(\zeta\omega)_d$, Fig. 6a, than versus ζ_d, Fig. 6b. This was also true for the very low frequency data given in Fig. 5. It appears, therefore, that $(\zeta\omega)_d$ is the more suitable correlating parameter for frequencies less than about 3.6 rad/sec — a conclusion which, except for the applicable frequency range, is held in common with others.[3,4,11] Furthermore, the variation of ratings with $(\zeta\omega)_d$ appears, on the average, to fall within a band about one rating point wide, whose upper boundary is that of the cross-hatched region of Fig. 6a extended along the 9 curve. For ω_d's greater than 3.6 it appears that desirable dampings, viewed as either $(\zeta\omega)_d$ or ζ_d, should increase. However, this tentative conclusion requires later reconsideration because, in addition to the frequency differences, there is a pronounced jump in at least one of the φ/β-related parameters, $\omega_d^2|\varphi/\beta|$, associated with the high frequency data (e.g., see Fig. 2b).

SECTION III

EFFECTS RELATED TO $|\varphi/\beta|_d$

As indicated in Table I, there are a large variety of situations which can excite Dutch roll through the lateral-directional coupling afforded by L'_β/N'_β. Some of these possibilities were recognized by early investigators who made determined attempts at correlation with a variety of parameters before settling on their preference. The emergence of $|\varphi/v_e|_d$ as the presently preferred form[20,21] was preceded by consideration of $|\varphi/\beta|$[1,2,4,24]; $|p/\beta|$[23]; $|\varphi/\psi|$[4,24]; $|p/\psi|$, $|\dot{p}/\psi|$, $|\ddot{p}/\psi|$[4]; $|a_y/\beta|$, $|a_y/v_e|$[2]; and $|a_y/\psi|$.[4] However its acceptance is by no means complete[4,16] and it seems likely, in view of Table I, that specific influences now ascribed to $|\varphi/v_e|$ could be better described by parameters more directly associated with the tasks or effects being rated by the pilot. The difficulty in such a specific, and therefore varied, approach is that it can lead to a very complicated picture of lateral oscillatory requirements. If such a picture is really necessary, then it will have to be drawn; but it seems likely that there may be one or two predominant effects which, if properly identified, will pretty much delineate the total picture. With this hope in mind, let us examine some of the "$|\varphi/v_e|$ effects" in the current literature.

References 11 and 29 report results of fixed-base simulations where one of the assessment maneuvers was a rudder kick. The reduced data presented in Ref. 11 establish trends which show that for a given $|\varphi/v_e|$ and $1/T_{1/2} = 1.44(\zeta\omega)_d$, pilot rating deteriorates as $1/C_{1/2} = 9.1\zeta_d$ increases. In other words, for a given $(\zeta\omega)_d$ and $|\varphi/v_e|$ pilot rating is worse as ω_d is decreased (for $1.3 < \omega_d < 3.0$). The same trends were also observed in the Ref. 29 tests performed in the same simulator. In this instance, however, the investigator noted that corresponding trends with frequency did not occur when pilots rated the airplane's response to a step lateral gust input. His conclusion was that the rudder kick results were being influenced

by the increasing sensitivity of the rudder as ω_d was decreased. This conclusion was verified in a separate series of tests, which showed no significant change of rating with decreasing ω_d provided N_{δ_r} was reduced proportional to the reduced $N_\beta \doteq \omega_d^2$.

Examination of the literal forms for Items 3 and 4 of Table I shows that the results of Ref. 29, as outlined above, are consistent with the notion that the pilots were primarily rating the oscillatory bank angle response. Thus for step gust inputs at given values of $|\varphi/v|$ and $(\zeta\omega)_d$ the bank angle response envelope is independent of ω_d, as are the reported ratings. On the other hand, for rudder kicks the response envelope is proportional to $(N'_{\delta_r}/\omega_d^2)|\varphi/\beta|_d$, and the ratings vary accordingly. For this particular series of tests $|\varphi/\beta|$ was proportional to $|\varphi/v_e|$, therefore the reported "correlations" with $|\varphi/v_e|$ are good. However, such correlations would be completely misleading in situations having the tested values of $(N'_{\delta_r}/\omega_d^2)|\varphi/v_e|_d$ but different values of $(N'_{\delta_r}/\omega_d^2)|\varphi/\beta|_d$ (e.g., due to an airspeed change).

Another example of misplaced faith in $|\varphi/v_e|$ is found in the results reported in Ref. 30, again conducted in a fixed-base simulator. Here, values of both $|\varphi/\beta|$ and $|\varphi/v_e|$ were individually varied, through airspeed and altitude changes, for constant "good" values of $\omega_\varphi/\omega_d = 0.93$, $\omega_d = 3.29$, $\zeta_d = 0.13$, $T_R = 0.78$, $T_s = 20$, and $\kappa_{\dot\varphi} = 0.87$. The pilots separately rated four tasks "without using rudder inputs," and correlations for each task were attempted versus $|\varphi/\beta|$ and $|\varphi/v_e|$ with the conclusion that: "Correlation with φ/v_e is evident for all flight conditions and all pilot tasks." One pilot delivered an over-all rating for $|\varphi/\beta| \doteq 12$, $|\varphi/v_e| \doteq 0.58$ which was almost exactly the same as the one he gave for the same $|\varphi/v_e|$ (but $|\varphi/\beta| \doteq 4$) in flight[7] and was also in very good agreement with his and other "conservative" pilots' rating of Task II. Task II (one of four) required a 50° heading change in lateral air turbulence "...using a maximum bank angle of 45° and a moderate maximum roll rate." The simulated turbulence was scaled to $\sigma_{v_g} = 4$ ft/sec (rms) and had a spectral form given by

$$\Phi_{v_g} \propto \left|\frac{s + 0.58(U_o/1000)}{[s + (U_o/1000)]^2}\right|^2 \tag{1}$$

Remembering the pilot's chief concern with bank angle response as deduced from the earlier fixed-base simulations[11,29] discussed above, it seems pertinent to suppose a similar preoccupation in these tests. If so, we should expect reasonable correlation with the parameter $\sigma_\varphi/\sigma_{v_g}$ associated with Item 5 of Table I. To test this notion, notice that the first-order numerator of the simulated gust form given above (Eq 1) is roughly canceled by one of the denominator first-orders, so that the gust form assumed in deriving the approximate literal expression in Table I is reasonably applicable; and $\omega_g \doteq U_o/1000$. Then, for $(\zeta\omega)_d$ constant, $\omega_d = 3.29$, and letting G contain all the necessary constants,

$$G^2 \frac{\sigma_\varphi^2}{\sigma_{v_g}^2} = \frac{U_o\left|\frac{\varphi}{v}\right|^2}{1 + \left(\frac{U_o}{3290}\right)^2} = \frac{\left|\frac{\varphi}{\beta}\right|^2}{U_o\left[1 + \left(\frac{U_o}{3290}\right)^2\right]} \tag{2}$$

The averaged pilot ratings given in Ref. 30 are plotted versus the values of $G(\sigma_\varphi/\sigma_{v_g})$, computed from the corresponding values of U_o and φ/β, in Fig. 7a; Fig. 7b presents the same rating data versus the given values of $|\varphi/v_e|$. It is the author's opinion that $G(\sigma_\varphi/\sigma_{v_g})$ provides better correlation than $|\varphi/v_e|$. Furthermore, it enhances our understanding and offers a logical basis for using such data for design purposes.

For example, suppose that the correlation with φ/v_e were better (and it's probably fortuitous that it isn't), how or why should it be used, in the context of Task II, to establish design requirements? In the first place, $|\varphi/v_e|$ rather than $|\varphi/v|$ was originally suggested[2] to account for natural changes in random gust velocities with altitude. But in this series of tests there was no such adjustment of the gust input amplitude with simulated changes in altitude. On the other hand, the bandwidth of the gust input <u>was</u> changed with airspeed, but this effect appears in neither $|\varphi/v_e|$ nor $|\varphi/v|$. Finally, how could the data be used to predict ratings for different $(\zeta\omega)_d$'s than those tested — not an unreasonable design question. The original presentation, duplicated in Fig. 7b, offers no clue, but if we recognize that $\sigma_\varphi/\sigma_{v_g}$ depends on $(\zeta\omega)_d^{-1/2}$ (Item 5, Table I), then Fig. 7a

could conceivably be used for $\zeta\omega$'s other than that tested (provided $\zeta\omega$ is greater than the basic requirement already discussed). The point is that expedient use of an illogical parameter which provides seemingly good correlation of a specific set of data can be extremely misleading in a general sense.

In this instance, based on clues supplied by prior investigations, we can, it seems, pinpoint the source of the pilots' complaints and use fairly meaningful correlations. However, locating the source of concern is quite difficult, in general, because pilot comments are seldom directly interpretable in simple terms. Nevertheless they can offer important clues and are too often disregarded in the rush to get the data points plotted. For example, the transcribed pilot comments pertaining to the flight tests of Ref. 7 show a strong concern for the large rolling <u>accelerations</u> and the "touchy" rudder control associated with high φ/β configurations; however, the data are "correlated" using $|\varphi/\beta|_d$, at best a very incomplete measure of either effect. In this case the pilot, who also wrote the report (under pressure of a deadline), disregarded his own comments! This same pilot, as noted earlier, also flew the fixed-base simulator of Ref. 30 and delivered ratings consistent (based on φ/v_e) with the flight test ratings of Ref. 7. Obviously he was not concerned with roll acceleration of the simulator (not even included in the display) nor with rudder control (specific instructions not to use rudder) but probably with the bank angle excursions, as deduced above. The fact that his numerical rating, of what must have been a completely different set of circumstances, happened to coincide with his flight test rating is unfortunate. The coincidence lends an aura of realism to the simulation study which, in consideration of the above differences, is not justified.

The pilot of Ref. 7 is not alone in regarding roll acceleration as the motion quantity of interest. The same concern is shown, indirectly (pilot comments were not available to the author), in Ref. 4, which in fact concludes that the proper correlation parameter is the ratio of roll acceleration to yaw angle in the Dutch roll mode. Also, the pilot comments pertinent to the tests of Ref. 9 indicate (for the high φ/β, $\omega_\varphi/\omega_d = 1$ cases) that rudder sensitivity and roll velocity or acceleration rather than bank angle

are the chief complaints. This background leads us to regard most fixed-base simulations on the subject of φ/β effects with suspicion (possible exceptions will be considered later). Fortunately the flight test investigations already used to study the basic damping requirement were all φ/β-oriented and can also be used to study such effects.

Of the available data, those of Ref. 4 are by far the most exhaustive. Tests were run at a large variety of flight conditions covering Mach numbers between 0.55 and 0.95 and altitudes between 10,000 and 40,000 ft. The natural variations in the Dutch roll characteristics occurring in this region were augmented somewhat by selective activation of the autopilot. In contrast, the other data considered pertinent[3,7,9] (we are still concerned only with data of known "small" ω_φ/ω_d influences) were obtained in each case at a given condition of Mach and altitude, and heavy use was made of artificial stability augmentation to obtain variations in φ/β and damping. In view of the coverage afforded by the Ref. 4 data and the (author's) present judgment as to their validity, it seems incredible that this work has not been more thoroughly digested and used. Undoubtedly there were a number of different reasons advanced at the time by different authorities in the handling qualities area for disregarding these results. The author's own reasons, as best he can recall, were their incompatibility with the results of Ref. 2, now suspected to have been contaminated by ω_φ/ω_d effects; and the conviction that judging an <u>uncontrolled</u> oscillation and projecting such judgments to a rating of <u>handling</u> qualities was too great an abstraction for the pilot to make. (We now expect pilots to make even greater abstractions, e.g., from a fixed-base simulator to flight!) Both of the above reasons have lost whatever validity they ever had; the first because of the known importance of ω_φ/ω_d effects, the second partly because of the close correspondence between over-all ratings and ratings of the control-fixed oscillations of Ref. 3. Also, the present recognition of Dutch roll characteristics as nuisance effects perhaps renders such effects related to comfort, possible disorientation, conflicting cues, etc., observable in the simple oscillatory motions. While it is pretty obvious from Table I that there <u>can</u> be effects and situations related to high φ/β that will be considered more

than a "nuisance," it appears that these may be so isolated as to require only slight distortions of the "big picture" we hope to unveil.

In Ref. 4 the data are fitted by an empirical equation, which can be written

$$\ln\left(\frac{R-1}{2.5}\right) = \frac{-\zeta\omega + 0.0141A}{0.1205 + 0.01072A} \tag{3}$$

where R is the rating number and A, already defined as the body axis roll acceleration-to-yaw ratio, is given by

$$A \equiv \omega_d^2(1 + \zeta_d^2)\left|\frac{\varphi_b}{\psi_b}\right|_d \doteq \omega_d^2\left|\frac{\varphi_b}{\psi_b}\right|_d \tag{4}$$

The use of this parameter rather than the corresponding $(\omega_d^2)|\varphi/\beta|_d$ seems to have been prompted by inconsistent flight test measurements of φ/β. The use of measured body axis rates, converted to displacements, was convenient, accurate, and, perhaps, considered more meaningful. At any rate, the data actually taken correlate fairly well with the empirical expression as shown in Fig. 8. (The ranges of φ/β and φ/v_e listed are taken from the values of φ_b/β_b "deduced" in Ref. 4 from the measured φ_b/ψ_b and other "compatible" data.) Plotted in the same way in Fig. 9a are computed versus actual ratings of selected high $|\varphi/\beta|$ data points from Refs. 3, 7, and 9. In these cases the readily available parameter $|\omega^2(\varphi/\beta)|_d$, rather than an equivalent value of A, was used to evaluate the computed rating from a nomographic chart[4] of Eq 3. The data selected from Refs. 7 and 9 are all the conditions tested in the prescribed $N'_{\delta_a}/L'_{\delta_a}$ range which are <u>not</u> already plotted in Fig. 3. The Ref. 3 data are all those falling within the parameter ranges shown; some 37 data points (out of the total 132) which lie between the parameter range extremes of Figs. 1 and 9 are not shown on either plot. Fig. 9b presents the same data plotted against ratings obtained by linear interpolation in Fig. 8 of Ref. 3, which gives 3.5 and 6.5 boundaries as functions of $1/T_{1/2}$ and $|\varphi/v_e|$. Incidentally, linear interpolation is completely consistent with the manner in which the raw data were processed to obtain Fig. 8 of Ref. 3.

A comparison of Figs. 9a and 9b shows that, judging by the data lying outside the band of perfect correlation ±1, $|\omega^2(\varphi/\beta)|_d$ is a more universally applicable parameter than $|\varphi/v_e|_d$. In fact, although derived from a completely different set of data, Eq 3 seems to fit the particular Ref. 3 points about as well as the Ref. 3 derived fit itself. Furthermore, Eq 3 does a quite credible job on the Ref. 7 and 9 data, whereas the Ref. 3 fairings fail miserably. This failure is indicated, not only by the data outside the Fig. 9b band, but, more conclusively, by the considerably steeper than 45° trend shown by both the Ref. 7 and Ref. 9 points.

Since $|\omega^2(\varphi/\beta)|$ now seems to be in a preferred position, let's examine more closely the implications of Eq 3. Notice first that for a constant rating, R, partial differentiation yields

$$\partial(-\zeta\omega) + 0.0141\partial A = 0.01072 \ln\left(\frac{R-1}{2.5}\right)\partial A$$

or

$$\left.\frac{\partial(\zeta\omega)}{\partial A}\right]_{R=\mathrm{const}} = 0.0141 - 0.01072 \ln\left(\frac{R-1}{2.5}\right) \tag{5}$$

Thus, to maintain a given rating with increasing $A \doteq |\omega^2(\varphi/\beta)|$ requires an "addition" to $\zeta\omega$ proportional to the increase in A, with the constant of proportionality, itself, increasing as the desired constant rating is reduced. The Fig. 10 plot of Eq 5 shows that the form of this "additional" requirement is consistent with established physiological and psychological "laws." For example, neglecting the asymptotic character of Eq 5 at R = 1, 10 (an artifact of the truncated rating system used), it appears that the log of $\Delta\zeta\omega/\Delta|\omega^2(\varphi/\beta)|$ is essentially linear with rating. That is, the pilot is apparently sensitive to multiples of, rather than increments in, the value of the parameter — a Weber's law effect having its counterpart in numerous perceptual experiments. Also, the parameter itself is indicative of the integral of acceleration times time (i.e., $\Delta\zeta\omega \sim \Delta/T_{1/2}$), which is a reasonable metric of pilot discomfort or annoyance.[31] Regardless of such "physical explanations" which, it seems, can always be made at the time (and discarded later), the facts, represented by Figs. 8 and 9, certainly give strong support to the superiority of $|\omega^2(\varphi/\beta)|$ over $|\varphi/v_e|$ as a correlating parameter.

Now, if acceleration is what the pilot is objecting to, why isn't lateral acceleration (e.g., at the pilot's head) more appropriate than rolling acceleration? This question was seriously considered, and (unsuccessful) correlations with $|a_y/\dot{\psi}|$ were attempted in the Ref. 4 work. The "explanation" given in that reference for the final correlations with rolling rather than lateral acceleration is quoted, as follows: "The (lateral) acceleration ... is not what the pilot feels. He is not a rigid body ... rigidly attached to the airframe. The nature of his anatomy and of his attachment to the airplane are such that he receives some feel through his feet, hands, and back, but primarily through his ischial tuberosities (seat bones), which are in effect attached to the airframe through relatively heavy vertical springs, and through relatively light transverse springs. If the restraints were idealized to zero lateral restraint he would still feel the moment, $I_{x_p}\ddot{\phi}$, about his own body axis, as the reacting couple on his ischia, independent of height. The problem is further complicated inasmuch as the pilot's reaction ... must be by sight as well as by feel."

Additional data bearing on this question are contained in Ref. 32, which reports comfort ratings of lateral accelerations at the subject's head obtained through in-flight forced rolling oscillations at frequencies between 0.1 and 3.0 cps. Each of five pilots rated 30 second exposures to various acceleration levels at various frequencies according to the following scale:

a. Imperceptible or just noticeable, but entirely acceptable.

b. Definitely noticeable, but acceptable.

c. Unpleasant and unacceptable for more than short periods (acceptable for only short periods).

d. Definitely (entirely) unacceptable in any circumstance.

While the correlations contained in Ref. 32 are all shown only with respect to lateral acceleration, the basic data required to make comparisons between $\dot{p}$ and a_y are available. Figure 11 shows such comparisons, where it may be seen that in general the boundaries between ratings are more clearly defined (i.e., fewer points need be discarded, or crossed out) when plotted

versus $\dot{p}$ than versus a_y. These data show that $\dot{p}$ is as good as, or better than, a_y as a correlating parameter.*

If, then, based on all the above evidence, we accept the correlations of Figs. 8 and 9a, there is a concomitant implication on the faired, high frequency, "basic" dampings of Fig. 6a (lines 7, 10, 11, and 12). In effect, these lines are now driven into the central region when corrected for the high $|\omega^2(\varphi/\beta)|_d$ test conditions. That is, there is no apparent change in the basic $(\zeta\omega)_d$ requirement with frequency up to $\omega \doteq 6.5$ rad/sec. This conclusion appears to be completely divergent from those drawn by previous investigators.[11,20] Reference 20, reflecting the conclusions of Ref. 11, uses constant $\zeta\omega \doteq 0.21$ as the low φ/v_e damping requirement for $\omega < 2.6$ rad/sec and constant $\zeta \doteq 0.09$ for $2.6 < \omega < 4.5$; beyond $\omega = 4.5$ (for low φ/v_e) it is suggested that the required ζ be increased by $\partial\zeta/\partial\omega \doteq 0.1$. The conclusion of Ref. 11 is based partly on fixed-base simulations (which later results[29] put in question — see above) and partly on a re-examination of the data of Refs. 1 and 2, both of which have been excluded from the present study because of unknown $N'_{\delta_a}/L'_{\delta_a}$ characteristics. The additional recommendation of Ref. 20 regarding frequencies greater than $\omega = 4.5$ is based on speculations concerning the pilot's ability to control poorly damped Dutch roll frequencies approaching 1 cps. But such control is completely inconsistent with our present picture of the Dutch roll motions (especially high frequencies) as anything more than a nuisance. Nevertheless, requiring an increasing ζ_d with increasing ω_d is also a feature of the "additional" damping requirement of Eq 5 for a constant $|\varphi/\beta|_d$. That is, from Eq 5, for a rating, R, of 3.5 and constant φ/β,

$$\partial(\zeta\omega) = 0.0141\ \partial A = 0.0141\ \partial\left|\omega^2 \frac{\varphi}{\beta}\right|$$

$$\frac{\partial(\zeta\omega)}{\partial\omega} = 0.0282\ \omega\left|\frac{\varphi}{\beta}\right| \qquad (6)$$

*The above defense of $\dot{p}$ rather than a_y as perhaps the more appropriate parameter does not necessarily extend to conditions other than those associated with Dutch roll oscillations. For situations where large side forces can develop, as for example in engine failures during supersonic flight, side acceleration seems to provide the dominant influence.[33]

Whether or not the most universal form of correlation is in terms of the "basic" plus "additional" effects so far suggested is a moot point; but the preponderance of applicable experimental evidence seems to support such a partitioning. Nevertheless, other less universal but perhaps more specifically important considerations must not be lost track of. For example, we have already noted the good correlation obtained with the parameter $\sigma_\varphi/\sigma_{v_g}$ in fixed-base simulator evaluations of rough-air handling qualities.[30] Correlations based on $\sigma_{\dot p}/\sigma_{v_g}$ (Item 5, Table I) shown in Fig. 12, for <u>limited</u> flight data[7] are similarly successful ($\sigma_\varphi/\sigma_{v_g}$ is not); in fact, slightly more so than the corresponding correlations in Fig. 9a. Other considerations (i.e., Table I) may override the simple "big picture" so far established, e.g.,

1. For low values of N'_β (i.e., approaching neutral stability) $|\omega^2(\varphi/\beta)| \doteq \cancel{N'_\beta}(L'_\beta/\cancel{N'_\beta})$ will not be a good indicator of piloting problems. In such cases it is questionable whether any amount of Dutch roll damping will eliminate undesirable, high L'_β/N'_β effects due to rudder inputs (inadvertent or trim) or thrust asymmetries, or aggravated by aerodynamic or inertial coupling. The basic reason for the retention of the awkward notation $|\omega^2(\varphi/\beta)|_d$, rather than an equivalent $|\dot p/\beta|_d$, is that it serves to remind us of this and other limitations on its applicability. There are additional considerations applying to the low N'_β case which are discussed in the next section.

2. For real approach and landing situations, and perhaps for low values of $|\omega^2(\varphi/\beta)|_d$, the pilot becomes much more concerned with the roll displacement than with the roll acceleration. This is especially true when ground clearance is involved, as in the decrab maneuver. Such situations are undoubtedly amenable to valid fixed-base simulation.[13]

3. In some special cases where the usual phase relationships between ψ and β are not maintained (e.g., for high

$(g/U_o)(L'_\beta/N'_\beta)T_R$ — see Item 1b, Table I), pilot discomfort or annoyance may not[4] be truly reflected by $|\omega^2(\varphi/\beta)|_d$.

SECTION IV

EFFECTS RELATED TO ω_φ/ω_d

Dutch roll motions can, of course, be excited by aileron-only control of the bank angle. When this happens, the Dutch roll characteristics become inextricably associated with the primary control mode, and their continued classification as a "nuisance" is then dubious. Consider the roll transfer function, φ/δ_a, given in Item 11 of Table I. Clearly, when $\omega_\varphi/\omega_d \neq 1$ and $\zeta_\varphi \neq \zeta_d$ the "classical" single-degree-of-freedom roll response given by (for small $1/T_s$)

$$\frac{\varphi}{\delta_a}(s) \doteq \frac{L'_{\delta_a}}{s\left(s + \frac{1}{T_R}\right)} \tag{7}$$

no longer applies. Now, the rolling velocity induced by an aileron input contains not only the "pure" roll-subsidence component, but an additional oscillatory component whose magnitude depends largely on ω_φ/ω_d (see Item 2, Table I). Thus, even though the pilot disregards the resulting yawing and sideslipping motions as "nuisances," he must be aware of and control the Dutch roll motions which appear in roll rate and bank angle. In so doing he runs into two predominant "ω_φ/ω_d effects." The first of these is the difficulty in accurately controlling (tracking) bank angle when $\omega_\varphi/\omega_d > 1$; the second is the oscillatory roll rate following step aileron inputs for $\omega_\varphi/\omega_d \neq 1$. Both effects are well supported by theoretical analyses and experimental handling qualities data[6–11,15,27,34]; and Fig. 13 illustrates their influence on pilot rating. The main purpose of the assembled data is to show that fixed-base simulation results are in generally good agreement with flight test results. Of interest too is the fact that there is reasonable correspondence among the results regardless of extremes in the maneuvering tasks and flight conditions (compare Refs. 8 and 34). Finally, Fig. 13b shows that for small (positive or negative) values of $(\omega_\varphi/\omega_d)^2$ opinion ratings seem to be pretty much independent of otherwise important

parameters such as ζ_d and T_R.[35] This suggests that the dominant effect in this region is the extreme cross-coupling which occurs for values of $(\omega_\varphi/\omega_d)^2$ less than 0.5[6] (more about this later).

Another kind of effect is that associated with a given ω_φ/ω_d at a low value of $|\varphi/\beta|_d$. Note from the approximate expressions for $|\varphi/\beta|_d$ and $\omega_\varphi^2/\omega_d^2$ (Items 1a and 11, respectively, of Table I) that a specified value of $\omega_\varphi/\omega_d \neq 1$ requires much larger values of $N'_{\delta_a}/L'_{\delta_a}$ for low than for high $|\varphi/\beta|_d$. Accordingly, in the Ref. 7 tests for a given value of ω_φ/ω_d the pilot's complaints about aileron yaw steadily increased (as did his rating number) as φ/β decreased (below the values of Fig. 13). These complaints were directed at the required use of the rudder to maintain coordination (Item 7, Table I) and were especially vociferous when unconventional cross-coordination, associated with large favorable yawing moments (ω_φ/ω_d greater than one and $N'_{\delta_a}/L'_{\delta_a}$ positive), was called for. Similar comments appear in Ref. 34 and in Ref. 8 which noted, in comparing a conventional center stick and pedals with a three-axis wrist-pivoted side stick, that "where cross-controlling was required, the pilots criticized the side-arm controller because of awkwardness of coordination of rudder and aileron." On the other hand, the data of Ref. 33 show an opposing trend in that favorable yawing moments are more desirable than adverse (zero is still most preferable). This bias is traceable to the improved control over transients resulting from the abrupt loss of a critical engine. The pilot-imposed criterion for a rating between 1 and 3.5 was that "...the resulting sideslip angle should not exceed 5° with no corrective rudder applied and with aileron used to maintain wings-level flight."

Yet another effect can be illustrated by the data of Ref. 30. You will recall that the pilot was given, and separately rated, four tasks, one of which has already been discussed in connection with Fig. 7. Task III of the series was "from 1g level flight (to) accomplish one 360° roll and stabilize straight and level." Rudder and elevator were to remain fixed and maximum aileron used was limited to one quarter that available. This task, which combines elements of both tracking and response to step aileron inputs should be susceptible to ω_φ/ω_d-like correlations. But the test value of ω_φ/ω_d = 0.93, noted earlier, is so close to unity that no real influence can

be expected on this count. However, when $\omega_\varphi/\omega_d \doteq 1$, the Dutch roll can still be excited by $\zeta_\varphi \neq \zeta_d$.[15] To check this possibility, values of ζ_φ were computed from the tabulated derivatives supplied in Ref. 30 and plotted versus the given average ratings; Fig. 14a shows the result along with the faired data of Ref. 15. The latter were obtained for slightly different conditions, viz., $1/T_s = 0$, $1/T_R = 2.5$, $\omega_d = 2.0$, $\zeta_d = 0.1$, $\omega_\varphi/\omega_d = 1.0$ (compare with Ref. 30 conditions, p. 9), and the three-pilot averaged minimum rating (at $\zeta_\varphi = \zeta_d$) was about 2.3. The fairing shown in Fig. 14a is shifted from that in Ref. 15 to a minimum rating of 3.5 at $\zeta_\varphi = \zeta_d$. On the whole the agreement between the two sets of data is pretty good, and the general correlation of the Ref. 30 ratings with ζ_φ seems evident. For comparison Fig. 14b supplies the correlation with $|\varphi/v_e|$ advanced in Ref. 30.

Another influence not to be lost sight of is the effective change in rudder-fixed rolling power with ω_φ/ω_d. Notice from Item 11 of Table I that the d.c. gain ($s \rightarrow 0$) of the roll-to-aileron transfer function is proportional to $L'_{\delta_a}(\omega_\varphi/\omega_d)^2$. For situations where ω_φ and ω_d are larger than the crossover frequency associated with closed-loop operation (and T_R is smaller[35]) this gain is the effective gain and variations from some optimum level will adversely affect pilot opinion.[35] For ω_φ, ω_d below the crossover region, the effective gain is just L'_{δ_a}. This brings up the additional point that in general the severity of the ω_φ/ω_d effect on <u>closed-loop</u> handling qualities depends intimately on the location of the ω_φ, ω_d pair with respect to the desired crossover region. Initial consideration[6] of such effects assumed the crossover would be near $1/T_R$ and proposed that the parameter $\omega_d T_R$ be included in the complete specification of "ω_φ/ω_d effects." Present indications are[35] that crossover is not simply related to $1/T_R$, but is more-or-less constant in the neighborhood of 2 ± 0.5 rad/sec.

An additional important "ω_φ/ω_d effect" just beginning to be recognized is that associated with the task of maintaining lateral flight path alignment as in landing approach. In these circumstances the basic metric of performance is the dominant time constant of the "outer" heading control loop (Item 12, Table I); that is, the faster (within limits) the closed-loop control of heading becomes, the better the pilot likes it. Such

effects have been studied analytically[16,36,37] and the results compared with fixed-base simulations[16] and flight test.[36] The following is a brief resume of these studies.

The basic closed-loop situation involves control of both bank angle and heading with aileron (use of rudder is an undesirable complication* and control of lateral flight path, y, boils down to heading, ψ, control[16]). This multiple-loop problem is tackled by first closing the bank angle "inner" loop ($\varphi \rightarrow \delta_a$) and then using the result as the "outer" loop ($\psi' \rightarrow \delta_a$) characteristic denominator as illustrated in the root loci of Fig. 15 (the single prime denotes that one inner loop has already been closed, the double primes are for two loops closed, following the conventions established in Ref. 41). That is, the symbols (▮) denoting the $\varphi \rightarrow \delta_a$ closed-loop characteristics become the poles (symbol ✕) of the $\psi' \rightarrow \delta_a$ loop. The dominant heading control time constant (which corresponds approximately to the inverse of the gain crossover frequency, ω_c) is limited by stability considerations and is usually so small that the pilot cannot employ effective lead (heading control is always a low frequency mode). More specifically, referring to Fig. 15b it may be seen that the limiting value of ω_c is set by the necessity for avoiding instability at ω_φ'' (i.e., having adequate gain and phase margins). Further, the extent to which heading gain (and crossover frequency) can be increased depends on the value of $(\zeta\omega)_\varphi'$, which in turn (Fig. 15a) is most strongly influenced by the basic value of $\zeta_\varphi\omega_\varphi$ (Item 11, Table I). Figures 15c and 15d show a similar dependence of the achievable heading time constant on $1/T_{\varphi_1}$, for situations where the φ/δ_a numerator is nonoscillatory (i.e., $\omega_\varphi^2 \equiv 1/T_{\varphi_1}T_{\varphi_2}$). Finally, Fig. 16** shows the correlations obtained[36] using the above basic φ/δ_a numerator characteristics as metrics. The correlations of Ref. 16 are not as conclusive since heading control was not the only task; nevertheless, indications are that ω_c's less than about 0.3 were considered objectionable, a value in surprisingly good agreement with the conclusions implied in Fig. 16.

*And may be ineffective (Item 13, Table I) in affording improved closed-loop control of Dutch roll yaw and sideslip.

**These data, obtained in variable-stability-helicopter flight tests, are the only systematic results bearing on this problem known to the author; they are presented here as examples of simila[illegible]ects which also occur for conventional airplanes.

This brings up another point. We have already seen that negative values of ω_φ^2 are generally objectionable (Fig. 13b). Furthermore, we can infer from Fig. 15c that a prime objection to such characteristics is the resulting negative value of $1/T_{\varphi_1}$. That is, mentally transposing $1/T_{\varphi_1}$ to the right half-plane of Fig. 15c, it is clear that, with the usual small values of the $1/T_s$ spiral mode associated with conventional airplanes (e.g., Fig. 15a), closure of the φ loop will result in almost immediate instability, characterized by a first-order divergence near $1/T_{\varphi_1}$ (similar to the altitude–speed divergence which occurs for elevator control of altitude for speeds below minimum drag[40]). Such situations are most prone to occur in practice when the directional stability, N_β, is very low (as it is for the case pictured in Fig. 15c). Under such circumstances, otherwise small values of adverse yaw are almost certain to incur negative values of $1/T_{\varphi_1}$.* For sufficiently small negative values, the airplane may still be controllable,[27] but will be heartily disliked and undoubtedly dangerous. This will of course be true even for situations where the "dynamic" directional stability, N'_β, still has a reasonable positive (stable) value. In effect, the pilot, by trying to closely control bank angle, eliminates the stabilizing effect of the $(I_{xz}/I_z)L_\beta$ term appearing in $N'_\beta \doteq \omega_d^2$ and substitutes the destabilizing $-(N_{\delta_a}/L_{\delta_a})L_\beta$ effect appearing in ω_φ^2. Clearly, the lower limit on allowable N_β must recognize these facts. That is, the minimum value of N_β must always be sufficient to guarantee that neither ω_φ^2 nor ω_d^2 become negative.

Another aspect of low directional stability is the possibility that, in combination with high positive $(N'_p - g/U_o)$, it may result in natural (i.e., airframe only) coupling of the spiral and roll subsidence modes into a low frequency oscillation.[5] Such "lateral phugoid" modes are usually poorly damped and generally difficult to control (an example is given in Ref. 16). They occur quite rarely and are only mentioned here as situations which, apparently, should generally be avoided for the retention of good handling qualities.

A more common problem associated with low directional stability and large values of $(N'_p - g/U_o)$ is the difficulty of obtaining good aileron-

*Recognize[5] that ω_φ^2 or $1/T_{\varphi_1}T_{\varphi_2} \doteq N_\beta + Y_v N_r - (N_{\delta_a}/L_{\delta_a})L_\beta$.

only turn entries, because of high induced sideslip.[13,16,43] In general, increased $(\zeta\omega)_d$ is of little direct help in such situations, which are however relieved by "unconventional" augmentation (e.g., "shaped" δ_a to δ_r or $\dot{\beta}$ to δ_r).

In summary, the various effects discussed above are:

1. Roll control (closed-loop) dynamic difficulties associated primarily with $\omega_\varphi/\omega_d > 1$ and, for $\omega_\varphi/\omega_d = 1$, $\zeta_\varphi \neq \zeta_d$; and dependent on ω_d relative to crossover.

2. Roll oscillations in response to aileron inputs associated with $\omega_\varphi/\omega_d \neq 1$ and also, for $\omega_\varphi/\omega_d = 1$, $\zeta_\varphi \neq \zeta_d$.

3. Rudder activity, primarily dependent on $N'_{\delta_a}/L'_{\delta_a}$, to prevent uncoordinated yawing and sideslipping motions.

4. Gain changes proportional to $(\omega_\varphi/\omega_d)^2$ for ω_d greater than crossover.

5. Heading control difficulties characterized by low values of $(\zeta\omega)_\varphi$ or $1/T_{\varphi_1}$.

6. Special problems associated with very low static directional stability.

This is a pretty complicated picture of what started out to be a simple "additional" consideration on the required Dutch roll damping. However, there are certain major requirements-oriented general conclusions that can be drawn from the various applicable experiments and analyses, as follows:

1. In general, $N'_{\delta_a}/L'_{\delta_a} \doteq 0$ is preferred. Possible exceptions are low ζ_d cases with sufficient $|\varphi/\beta|$ to make the open-loop roll oscillation noticeable; then $\omega_\varphi/\omega_d < 1$ is helpful[7,8] because it permits the pilot to damp the Dutch roll using ailerons only.

2. Increased yaw damping (affecting both ζ_d and ζ_φ) is always helpful when $(\omega_\varphi/\omega_d)^2$ lies between about 0.5 and 1.5; for values outside this range it appears to be ineffective.[8]

3. Fixed-base simulations including adequate displays and performed by properly briefed, experienced test pilots can be successfully used to explore all "ω_φ/ω_d effects" of major concern.

SECTION V

CONCLUSIONS

A major conclusion of the studies contained in this report is that handling qualities parameters must be carefully chosen to reflect the pilot's real concern. This deceptively simple and on-the-whole acceptable rule is loaded with dynamite! In the first place, as demonstrated by many illustrative examples herein, it is no easy task to discover or to infer the root causes of the pilot's difficulties (this is particularly true when pilot comments are not elicited or heeded). In the second place, there are a large number of effects which, depending on the circumstances involved, can be troublesome. Thus, paying strict attention to the rule, while it will eventually clarify and improve our understanding, tends initially to be confusing rather than enlightening. The following specific conclusions, drawn from the studies presented, will hopefully dissipate some of this confusion:

1. Dutch roll motions are generally not desired or commanded by a pilot and he regards them as a nuisance.

2. The required Dutch roll damping can be separated into "basic" and "additional" components.

3. The "basic" damping requirement appears to be best specified in terms of total damping, $(\zeta\omega)_d$, rather than damping ratio, ζ_d.

4. A satisfactory (rating of 3.5) basic value of $(\zeta\omega)_d$ seems to lie between 0.2 and 0.3, corresponding to $T_{1/2}$ between 3.5 and 2.3 sec, for all frequencies between about 0.8 and 6 rad/sec (Fig. 6a).

5. An unsatisfactory (rating of 6.5) basic value of $(\zeta\omega)_d$ seems to be about zero for the above frequencies.

6. To maintain a given rating in the face of increasing roll-yaw coupling due to dihedral requires an "additional" increase in $(\zeta\omega)_d$.

7. This "additional" $\Delta(\zeta\omega)_d$ appears to be directly related to the ratio of roll acceleration to sideslip appearing in the Dutch roll mode, as given by Eq 5.

8. Fixed-base simulations of such "additional" effects, to be successful, must employ adequate displays of roll angle, rate and acceleration; and the pilots involved should have experience with similar values of $(\dot{p}/\beta)_d$ in flight or in valid moving simulators (author's opinion).

9. For low values of $(\dot{p}/\beta)_d$ and especially for flight near the ground (as in landing approach or terrain following) the roll angle rather than acceleration may more appropriately reflect the pilot's concern (author's opinion). If this is true, then fixed-base simulation is a valid tool for investigating such circumstances.

10. Where the usual phase relationships between ψ and β are violated, pilot discomfort or annoyance may not be truly reflected by $(\dot{p}/\beta)_d$.

11. Coupling effects due to aileron yaw are generally deleterious as regards rating. "Additional" damping is generally helpful in such cases except for values of the $(\omega_\varphi/\omega_d)^2$ coupling parameter outside the range between about 0.5 and 1.5.

12. For low $(\zeta\omega)_d$ cases with sufficient $|\varphi/\beta|$ to make open-loop roll oscillations apparent to the pilot, $\omega_\varphi/\omega_d < 1$, implying "adverse" aileron yaw, improves the rating.

13. Good heading control seems to require a closed-loop crossover frequency, ω_{co}, higher than about 0.3. For those situations where use of the rudder to improve heading response is undesirable or not helpful, this can be roughly translated to mean that the aileron roll

numerator damping, $(\zeta\omega)_{\varphi}$, or minimum inverse time constant, $1/T_{\varphi_1}$, must be greater than about 0.4.

14. The lower limit on directional stability appears to be set by the requirement that ω_{φ}^2 remain positive or that roll–spiral coupling into a "lateral phugoid" be avoided.

15. Aileron-only turns at high lift require special consideration of (additional) $N_p' - g/U_0$ effects which cannot in general be countered by increased $(\zeta\omega)_d$.

16. All of the foregoing aileron effects (11 – 15) are amenable to investigation in fixed-base simulators.

17. Effects other than those specifically considered in this report (e.g., Table I) will have pertinence[16] for special conditions or configurations.

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TABLE I

LATERAL CONTROL AND RESPONSE CONSIDERATIONS

ITEM	DESCRIPTION	APPROXIMATE LITERAL EXPRESSIONS
1	Dutch roll modal response ratios a. Roll-to-sideslip	$\left\lvert\frac{\varphi}{\beta}\right\rvert_d \doteq -\frac{L'_\beta}{N'_\beta}\frac{1}{\sqrt{1+\frac{1}{\omega_d^2T_R^2}}}$ $\measuredangle\left(\frac{\varphi}{\beta}\right)_d \doteq \tan^{-1}\frac{\omega_d\left[\left(\frac{L'_\beta}{N'_\beta}\right)\left(L'_p+2\zeta_d\omega_d\right)+L'_r\right]}{-L'_\beta+\zeta_d\omega_d\left[\left(\frac{L'_\beta}{N'_\beta}\right)L'_p+L'_r\right]+L'_rL'_p}$
	b. Heading-to-sideslip	$\left\lvert\frac{\psi}{\beta}\right\rvert_d \doteq \left\{1-2\frac{\left\lvert\left(\frac{g}{\omega}\right)\left(\frac{\varphi}{v}\right)\right\rvert_d}{\sqrt{1+\omega_d^2T_R^2}}+\left\lvert\left(\frac{g}{\omega}\right)\left(\frac{\varphi}{v}\right)\right\rvert_d^2\right\}^{1/2}$ $\measuredangle\left(\frac{\psi}{-\beta}\right)_d \doteq \tan^{-1}\frac{\omega_dT_R+2\zeta_d\left(1-2\zeta_d\omega_dT_R\right)}{X_d\omega_dT_R-1}-\tan^{-1}\frac{\omega_dT_R+2\zeta_d(1-2\zeta_d\omega_dT_R)}{X_d\omega_dT_R-1-(g/U_0)(L'_\beta/N'_\beta)T_R}$
2	Roll response due to step aileron	$\frac{p}{T_RL'_{\delta_a}\delta_a} \doteq \left(\frac{\omega_\varphi}{\omega_d}\right)^2e^{-t/T_s}-\frac{1+\omega_\varphi^2T_R^2}{1+\omega_d^2T_R^2}e^{-t/T_R}+\frac{\left(\frac{\omega_\varphi}{\omega_d}\right)^2-1}{\sqrt{1+\omega_d^2T_R^2}}e^{-\zeta_d\omega_dt}\sin\left(\omega_dt-\sin^{-1}\frac{1}{\sqrt{1+\omega_d^2T_R^2}}\right)$
3	Dutch roll bank-angle response due to step* side gust	$\varphi_d/\beta_{g_v} \doteq \lvert\varphi/\beta_v\rvert_de^{-\zeta_d\omega_dt}\sin\left[\omega_dt-\sin^{-1}\frac{1}{\sqrt{1+(1/\omega_d^2T_R^2)}}\right]$; $p_d \propto \omega_d\lvert\varphi\rvert_d$; $\dot p_d \propto \omega_d^2\lvert\varphi\rvert_d$
4	Dutch roll bank-angle response to step* rudder	$\frac{\varphi_d}{\delta_r} \doteq \left(\frac{N'_{\delta_r}}{\omega_d^2}\right)\left\lvert\frac{\varphi}{\beta}\right\rvert_de^{-\zeta_d\omega_dt}\cos\left[\omega_dt+\cos^{-1}\frac{\zeta_d-\omega_dT_R}{\sqrt{1+\omega_d^2T_R^2}}\right]$; $p_d \propto \left(\frac{N'_{\delta_r}}{\omega_d}\right)\left\lvert\frac{\varphi}{\beta}\right\rvert_d$; $\dot p_d \propto N'_{\delta_r}\left\lvert\frac{\varphi}{\beta}\right\rvert_d$
5	Mean-squared controls-fixed roll response due to random side gusts	$\frac{\sigma_\varphi^2}{\sigma_{v_g}^2} \doteq \frac{\omega_g}{2(\zeta\omega)_d}\frac{\left\lvert\frac{\varphi}{v}\right\rvert^2}{\left[1+\left(\frac{\omega_g}{\omega_d}\right)^2\right]}$ $\sigma_p^2 \doteq \omega_d^2\sigma_\varphi^2$; $\sigma_{\dot p}^2 \doteq \omega_d^4\sigma_\varphi^2$ where the gust spectrum is of the simplified form $\Phi_{v_g} = \lvert\kappa/(s+\omega_g)\rvert^2$; $\kappa = \sqrt{2\omega_g}\,\sigma_{v_g}$; $\omega_g \propto U_0$
6	Aileron-rudder control for steady sideslips	$\frac{\delta_a}{\delta_r} = -\frac{L'_{\delta_r}\left[1-\left(\frac{N'_{\delta_r}}{L'_{\delta_r}}\right)\left(\frac{L'_\beta}{N'_\beta}\right)\right]}{L'_{\delta_a}\left[1-\left(\frac{N'_{\delta_a}}{L'_{\delta_a}}\right)\left(\frac{L'_\beta}{N'_\beta}\right)\right]} \doteq -\left(\frac{L'_{\delta_r}}{L'_{\delta_a}}\right)\left(\frac{\omega_d^2}{\omega_\varphi^2}\right)\left[1+\left(\frac{N'_{\delta_r}}{L'_{\delta_r}}\right)\left\lvert\frac{\varphi}{\beta}\right\rvert_d\sqrt{1+\frac{1}{\omega_d^2T_R^2}}\right]$
7	Initial rudder and rudder rate required to hold $\beta = 0$ for step aileron	$\left(\frac{\delta_r}{\delta_a}\right)_0 = -\frac{N'_{\delta_a}}{N'_{\delta_r}}$; $\left(\frac{\dot\delta_r}{\delta_a}\right)_0 = \frac{L'_{\delta_a}}{N'_{\delta_r}}\left[1-\left(\frac{L'_{\delta_r}}{N'_{\delta_r}}\right)\left(\frac{N'_{\delta_a}}{L'_{\delta_a}}\right)\right]\left(\frac{g}{U_0}-N'_p\right)$
8	Rudder required to coordinate steady banked turns	$\frac{\delta_r}{\varphi_{ss}} = -\left(\frac{g}{U_0}\right)\left(\frac{N'_r}{N'_{\delta_r}}\right)\frac{\left[1-\left(\frac{N'_{\delta_a}}{L'_{\delta_a}}\right)\left(\frac{L'_r}{N'_r}\right)\right]}{\left[1-\left(\frac{N'_{\delta_a}}{L'_{\delta_a}}\right)\left(\frac{L'_{\delta_r}}{N'_{\delta_r}}\right)\right]}$
9	Bank angle in steady sideslip	$\frac{\varphi}{\beta} = -\frac{U_0}{g}\left\{Y_v-Y^*_{\delta_r}\left(\frac{N'_\beta}{N'_{\delta_r}}\right)\frac{\left[1-\left(\frac{N'_{\delta_a}}{L'_{\delta_a}}\right)\left(\frac{L'_\beta}{N'_\beta}\right)\right]}{\left[1-\left(\frac{N'_{\delta_a}}{L'_{\delta_a}}\right)\left(\frac{L'_{\delta_r}}{N'_{\delta_r}}\right)\right]}\right\}$
10	Pitch, roll-rate inertial and aerodynamic coupling	$\frac{p(s)}{P_0} = \frac{L'_\beta\left[\frac{(I_x-I_y)}{I_z}\right]\dot\theta(s)}{(s-L'_p)(s^2-N'_rs+N'_\beta)}$ $\left.\frac{p(t)}{P_0}\right]_{t\to\infty} \doteq \frac{-L'_\beta}{N'_\beta L'_p\left[\dot\theta(t)\right]_{t\to\infty}}$
11	Continuous control of bank angle with aileron	$\frac{\varphi}{\delta_a}(s) = \frac{L'_{\delta_a}\left(s^2+2\zeta_\varphi\omega_\varphi s+\omega_\varphi^2\right)}{\left(s+\frac{1}{T_s}\right)\left(s+\frac{1}{T_R}\right)\left(s^2+2\zeta_d\omega_ds+\omega_d^2\right)}$; $\left(\frac{\omega_\varphi}{\omega_d}\right)^2 \doteq 1-\left(\frac{N'_{\delta_a}}{L'_{\delta_a}}\right)\left(\frac{L'_\beta}{N'_\beta}\right)$; $2\left(\zeta_\varphi\omega_\varphi-\zeta_d\omega_d\right) \doteq \frac{L'_\beta}{N'_\beta}\left(N'_p-\frac{g}{U_0}\right)+\left(\frac{N'_{\delta_a}}{L'_{\delta_a}}\right)L'_r$ $2\zeta_\varphi\omega_\varphi \doteq \frac{N_{\delta_a}}{L_{\delta_a}}L_r-Y_v-N_r$
12	Closed-loop aileron control of heading	$\left.\frac{\psi}{\psi_c}\right]_{\substack{\varphi\to\delta_a\\ \psi\to\delta_a}} \doteq \frac{1}{(T_\psi s+1)}$ + less dominant higher order dynamics ; T_ψ = strong function of $\zeta_\varphi\omega_\varphi$ (or $1/T_{\varphi_1}$) (no literal expression available)
13	Yaw-rate-to-rudder control of Dutch roll damping	$\frac{r}{\delta_r}(s) = \frac{N'_{\delta_r}\left(s+\frac{1}{T_{r_1}}\right)\left(s^2+2\zeta_r\omega_rs+\omega_r^2\right)}{\left(s+\frac{1}{T_s}\right)\left(s+\frac{1}{T_R}\right)\left(s^2+2\zeta_d\omega_ds+\omega_d^2\right)}$; for $\left\lvert\left(\frac{g}{U_0}\right)L_p\right\rvert < \left\lvert\frac{L_p^3}{10}\right\rvert$, $\left(\frac{\omega_r}{\omega_d}\right)^2 \doteq \left(\frac{g}{U_0L'_p}\right)\frac{L'_\beta}{N'_\beta}$ (Ref. 5) for $\left\lvert\left(\frac{g}{U_0}\right)L_p\right\rvert \gg \left\lvert L_p^3\right\rvert$, $\left(\frac{\omega_r}{\omega_d}\right)^2 \doteq \frac{\left[-(g/U_0)L'_\beta\right]^{2/3}}{N'_\beta}$ (Ref. 25)

POSSIBLE HANDLING QUALITIES CONNOTATIONS
$\lvert\varphi/\beta\rvert$ or variants thereof have long been considered prime indicators of lateral-directional cross-coupling problems.[1-3] $\measuredangle\ \varphi/\beta$ may be indicative of possible conflicting cues. Note that for high L'_β/N'_β (i.e., L'_r terms negligible), $\tan(\varphi/\beta)_d \to 1/(\zeta_d + \omega_d T_R)$ for $\zeta\omega \ll L'_p \doteq -1/T_R$; for low L'_β (i.e., L'_r terms dominant), $\tan \varphi/\beta \to 1/(\zeta_d - 1/\omega_d T_R)$, implying that the sign can become negative.
$\lvert\psi/\beta\rvert$ considered as another possible source of conflicting cues. Notice that for low φ/v ($\doteq L'_\beta/U_0 N'_\beta$), $\psi/\beta = -1$ as in classic case. However, its possible degradation can be severe; for example, for $\varphi/v = 2$ deg/fps $= 0.035$ rad/fps, $\omega_d = 1$, $\omega_d T_R = 0.5$, $\zeta_d = 0.2$, $\lvert\psi/\beta\rvert$ becomes about 0.5, and $\measuredangle\ \psi/-\beta$ approaches 31 deg.
This complete expression shows the relative magnitude of the Dutch roll oscillation appearing in roll to be dependent on $(\omega_\varphi/\omega_d)^2$. For sufficiently low values of ω_φ/ω_d,[6,11] roll hesitation or reversal may occur; also, pilot rating is influenced by the relative magnitude of the oscillatory roll component.[10]
Corresponds to rolling motions following release from a steady sideslip, which is a standard flight test maneuver used to investigate and evaluate lateral oscillatory characteristics.
Pilots sometimes complain about "touchy" rudder control for high $\lvert\varphi/\beta\rvert$ configurations,[6] and also about the difficulty in establishing lateral-directional trim.[9]
A measure of the dominant uncontrolled rolling motions in rough air which undoubtedly contribute to the pilot's dislike of high $\lvert\varphi/v\rvert$ configurations.
For high $\lvert\varphi/\beta\rvert$, δ_a/δ_r can become uncomfortably high, so that deliberate sideslip maneuvers tend to saturate aileron control.[16] On the other hand, depending on available aileron controllability (e.g., near stall), it may be necessary to use rudder for roll control.
These two parameters combine to form a simplified picture of the rudder action required to maintain zero sideslip following a step aileron input.[16] By inference they also indicate the nature of the β time history for the rudder-fixed response to a step aileron.
Pilots sometimes complain about sign changes in δ_r/φ and find it difficult to accommodate to unconventional signs[7] (and magnitudes). Largely dependent on values of $N'_{\delta_a}/L'_{\delta_a}$.
For low values of this parameter, pilot cannot readily distinguish sideslipping conditions[12,14] and airplane motions tend to become uncoordinated — primarily a low speed (low side force) effect.
Indicative of <u>nonclassical</u> inertial coupling in which nose-down elevator inputs (producing negative $\dot{\theta}$) lead to violent departures from the "steady" roll rate, P_0.[26]
Closed-loop analyses of $\varphi \to \delta_a$[6,15] as the primary control loop reveal and explain piloting problems associated with $\omega_\varphi/\omega_d \neq 1$,[7,27] $\zeta_\varphi\omega_\varphi/\zeta_d\omega_d \neq 1$, and nonoptimum values of T_R.
Heading control with $\varphi \to \delta_a$ as an inner loop can be characterized (e.g., at approach speeds) by large values of T_ψ which result in a "sloppy" ground track.[16,36]
For low values of the ratio ω_r/ω_d, yaw-rate-to-rudder is very effective in damping Dutch roll oscillations; for values approaching (or greater than) unity, it is ineffective.[16,36,41] The ratio is strongly dependent on L'_β/N'_β and difficulties with high $\lvert\varphi/\beta\rvert_d$ configurations have been observed. Such difficulties are not always apparent on flight test airplanes, which may have auxiliary β information[7,9] presented to the pilot ($\beta \to \delta_r$ always works well to suppress Dutch roll oscillations).

	⊙ - Ref. 3	▽ - Ref. 8
		Pilot A
ω_d	1.63 - 1.99	1.57 - 1.90
$\lvert\phi/\beta\rvert$	2.55 - 3.00	2.90 - 2.95
$\lvert\phi/v_e\rvert$	.51 - .60	.58 - .59
$\omega_d^2\lvert\phi/\beta\rvert$	7 - 12	7 - 10
$N'_{\delta_a}/L'_{\delta_a}$	"Best"	Zero (Faired Data)

Letters designate pilot
Flagged symbols are for oscillatory ratings which differ from overall rating by one point or more

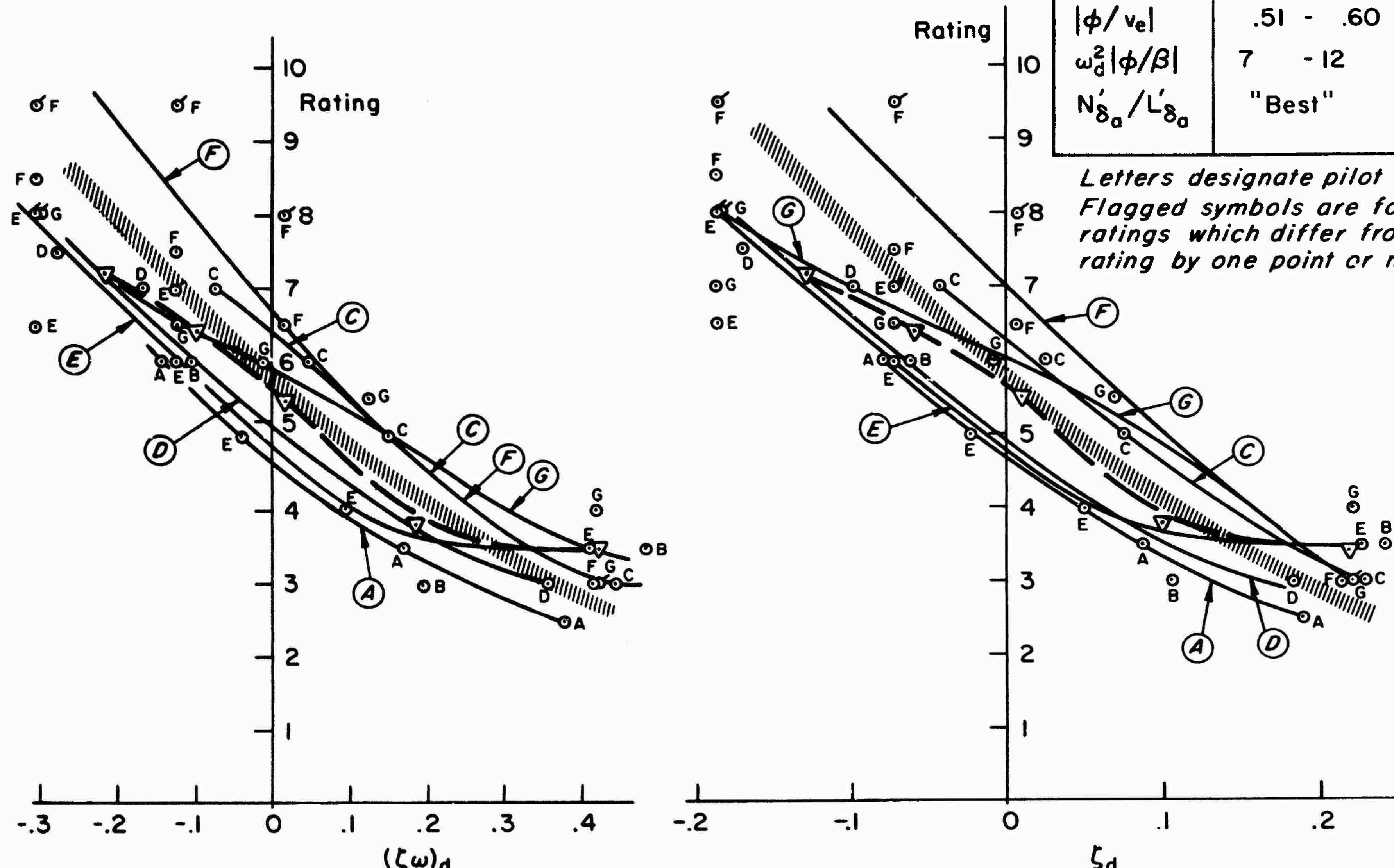


Figure 1. NASA Variable Stability F-86E Data
a) "Low Frequency"

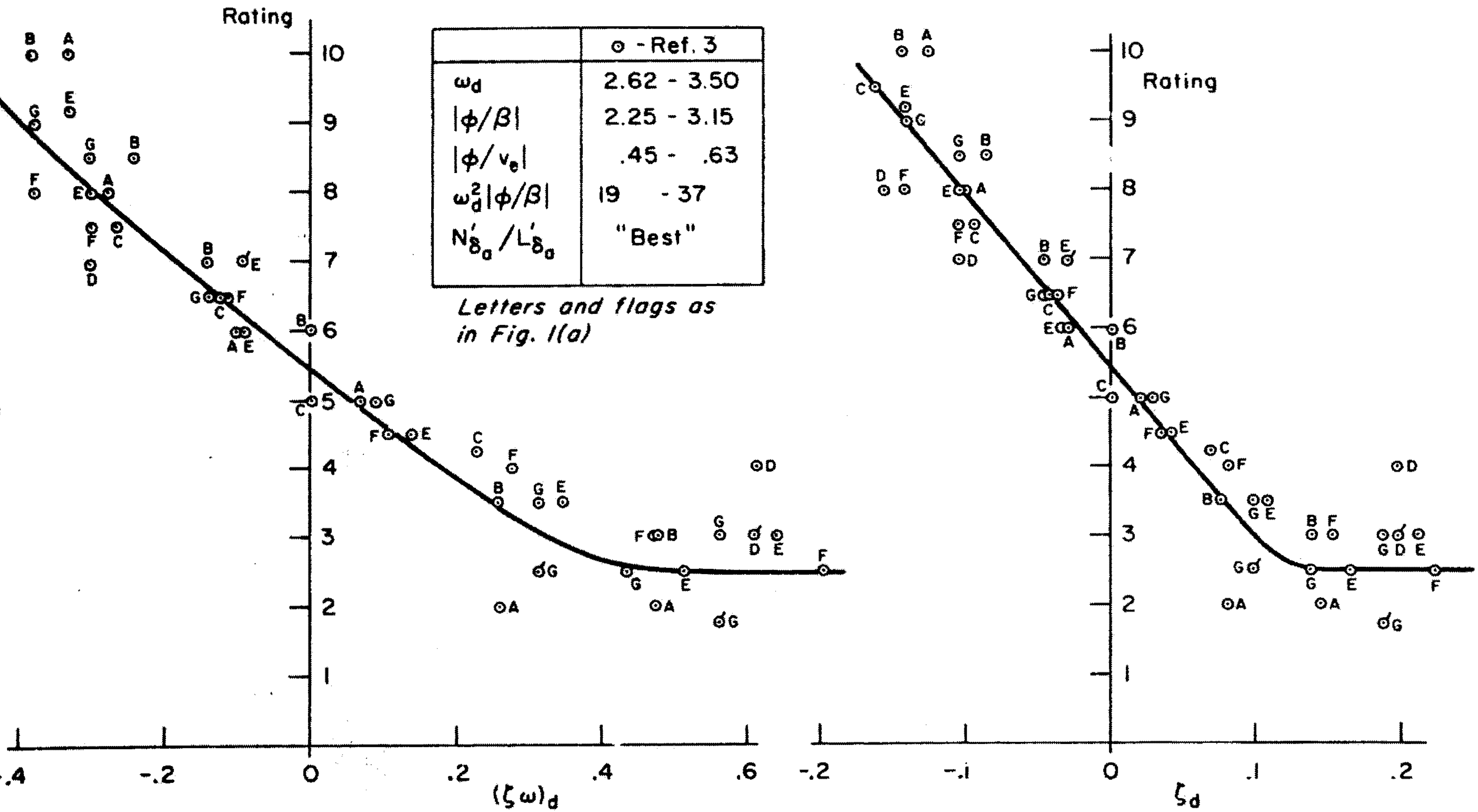


Figure 1 (concl'd). NASA Variable Stability F-86E Data
b) "High Frequency"

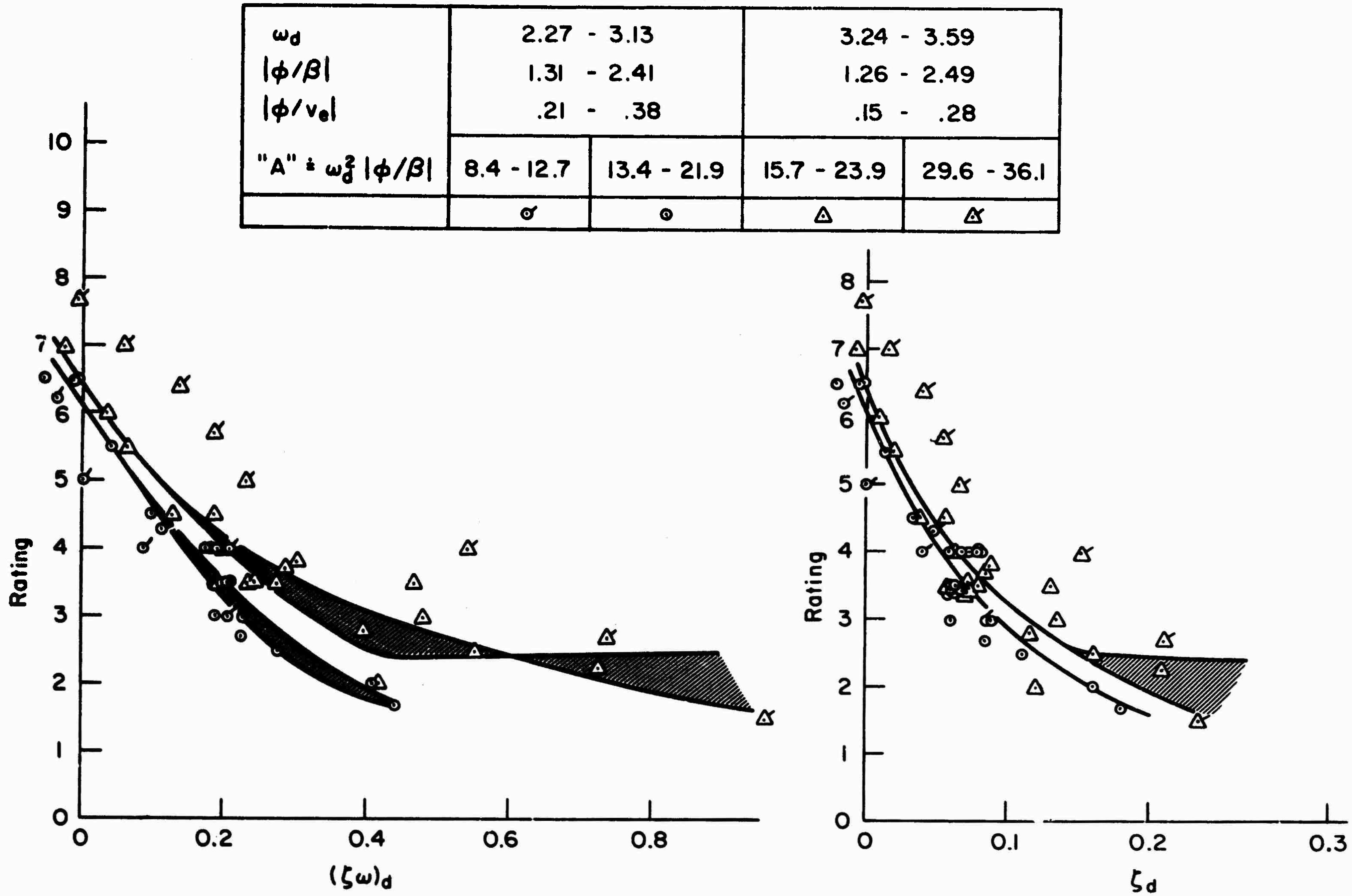


Figure 2. McDonnell (Ref. 4) Variable Stability XF-88A Data
a) "Low Frequency"

ω_d $\lvert\phi/\beta\rvert$ $\lvert\phi/v_e\rvert$	4.00 - 4.44 1.38 - 2.18 .16 - .21		5.00 - 5.25 1.48 - 1.75 .11 - .14	5.85 - 6.46 1.37 - 2.50 .10 - .19	
"A" $\div \omega_d^2 \lvert\phi/\beta\rvert$	25.6 - 29.3	48.9 - 55.2	38.5 - 48.7	49 - 65	69 - 99
	⊙	⊙'	△	⊡	⊡'

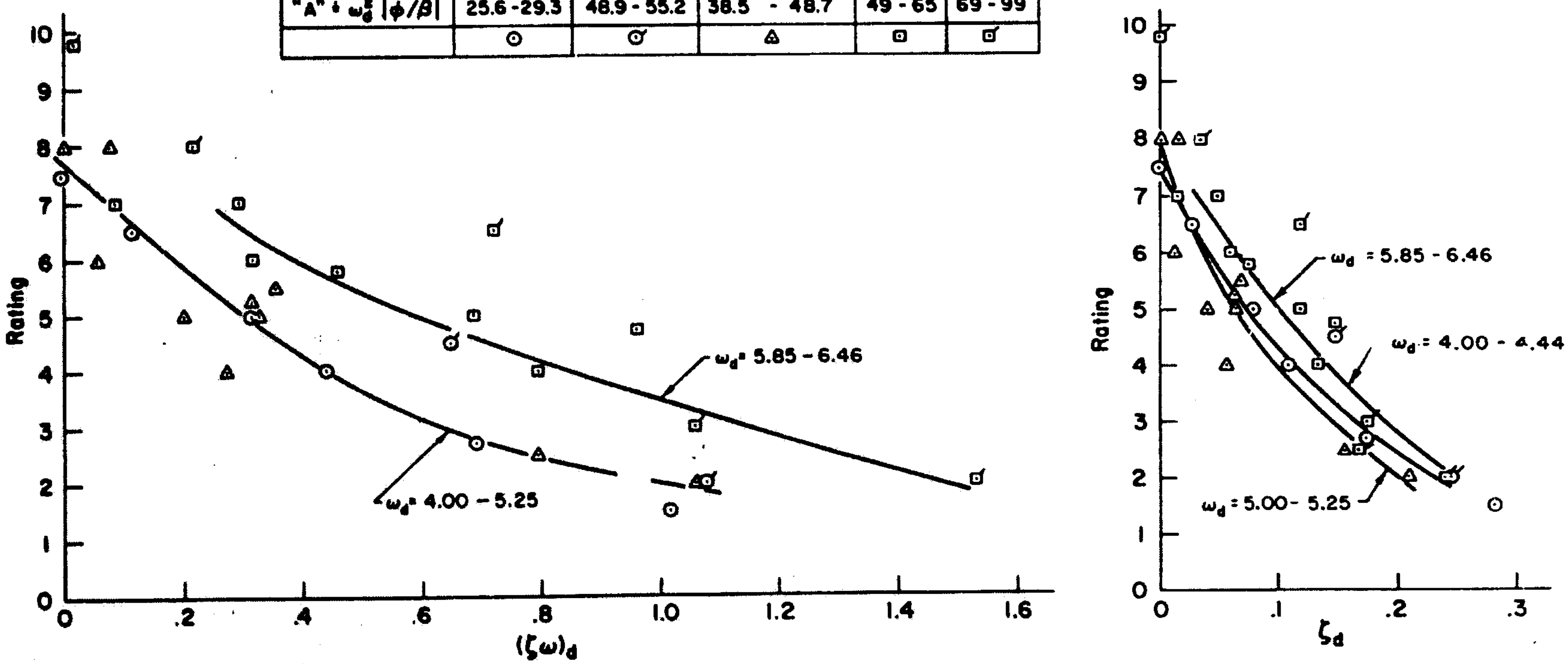
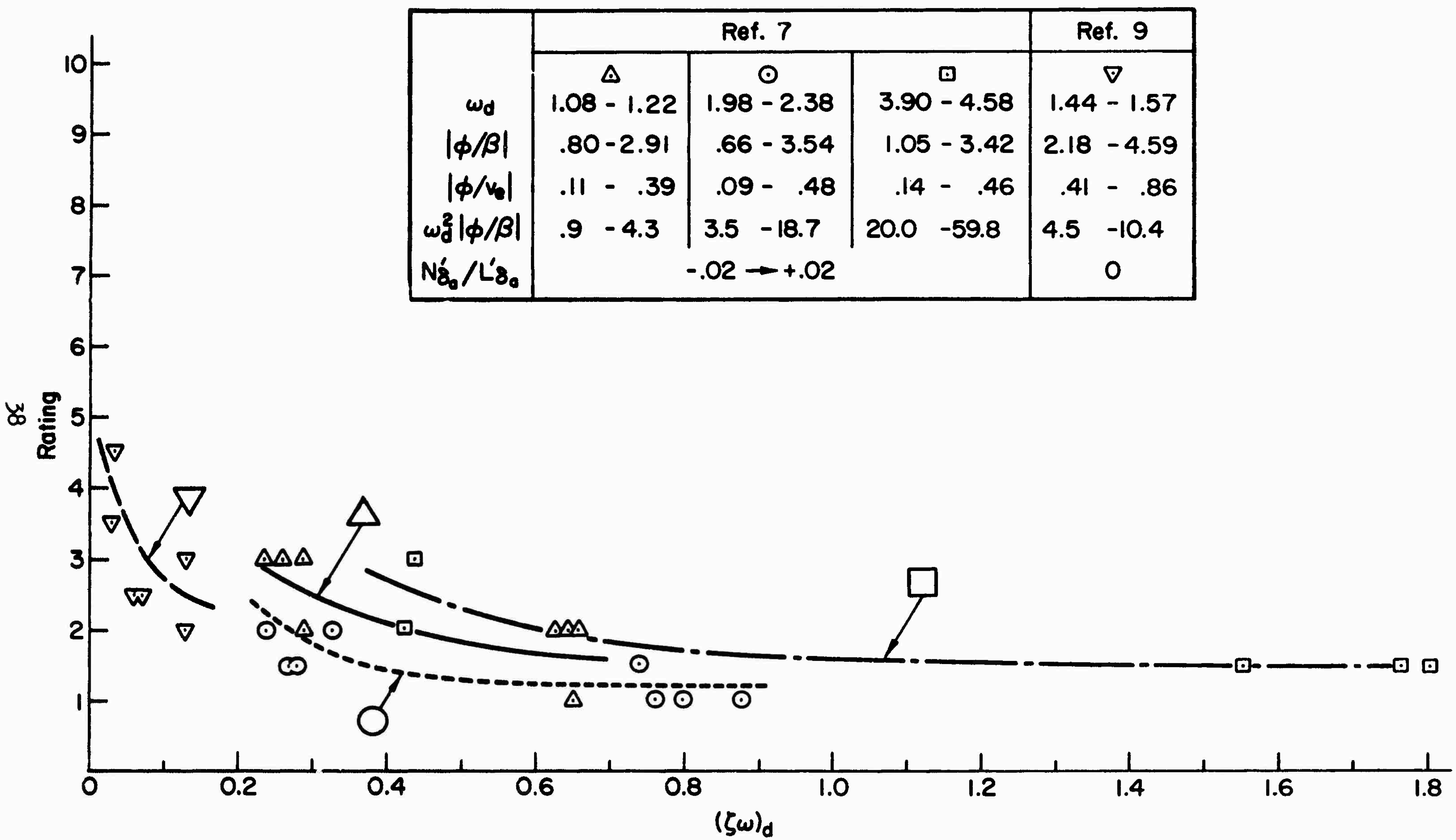
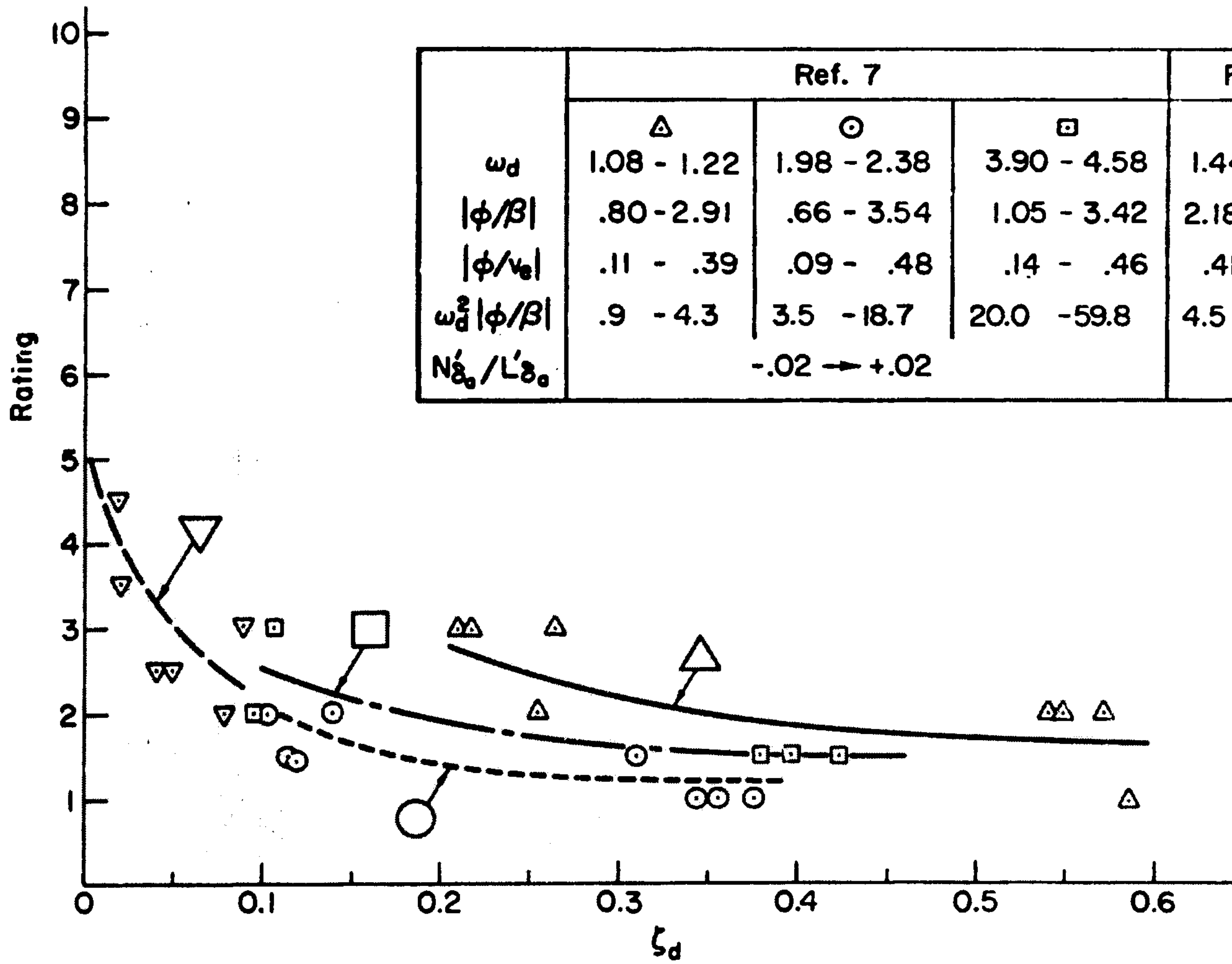


Figure 2 (concl'd). McDonnell (Ref. 4) Variable Stability XF-88A Data
b) "High Frequency"



	Ref. 7			Ref. 9
	△	⊙	⊡	▽
ω_d	1.08 - 1.22	1.98 - 2.38	3.90 - 4.58	1.44 - 1.57
$\lvert\phi/\beta\rvert$	.80 - 2.91	.66 - 3.54	1.05 - 3.42	2.18 - 4.59
$\lvert\phi/v_e\rvert$	.11 - .39	.09 - .48	.14 - .46	.41 - .86
$\omega_d^2\lvert\phi/\beta\rvert$	.9 - 4.3	3.5 - 18.7	20.0 - 59.8	4.5 - 10.4
$N'_{\delta_a}/L'_{\delta_a}$	-.02 → +.02			0

Figure 3. CAL Variable Stability T-33 Data
a) Ratings vs. $(\zeta\omega)_d$



	Ref. 7			Ref. 9
	△	⊙	⊡	▽
ω_d	1.08 - 1.22	1.98 - 2.38	3.90 - 4.58	1.44 - 1.57
$\lvert\phi/\beta\rvert$	.80 - 2.91	.66 - 3.54	1.05 - 3.42	2.18 - 4.59
$\lvert\phi/v_e\rvert$	.11 - .39	.09 - .48	.14 - .46	.41 - .86
$\omega_d^2\lvert\phi/\beta\rvert$	.9 - 4.3	3.5 - 18.7	20.0 - 59.8	4.5 - 10.4
$N'_{\delta_a}/L'_{\delta_a}$	-.02 → +.02			0

Figure 3 (concl'd). Variable Stability T-33 Data
b) Ratings vs. ζ_d

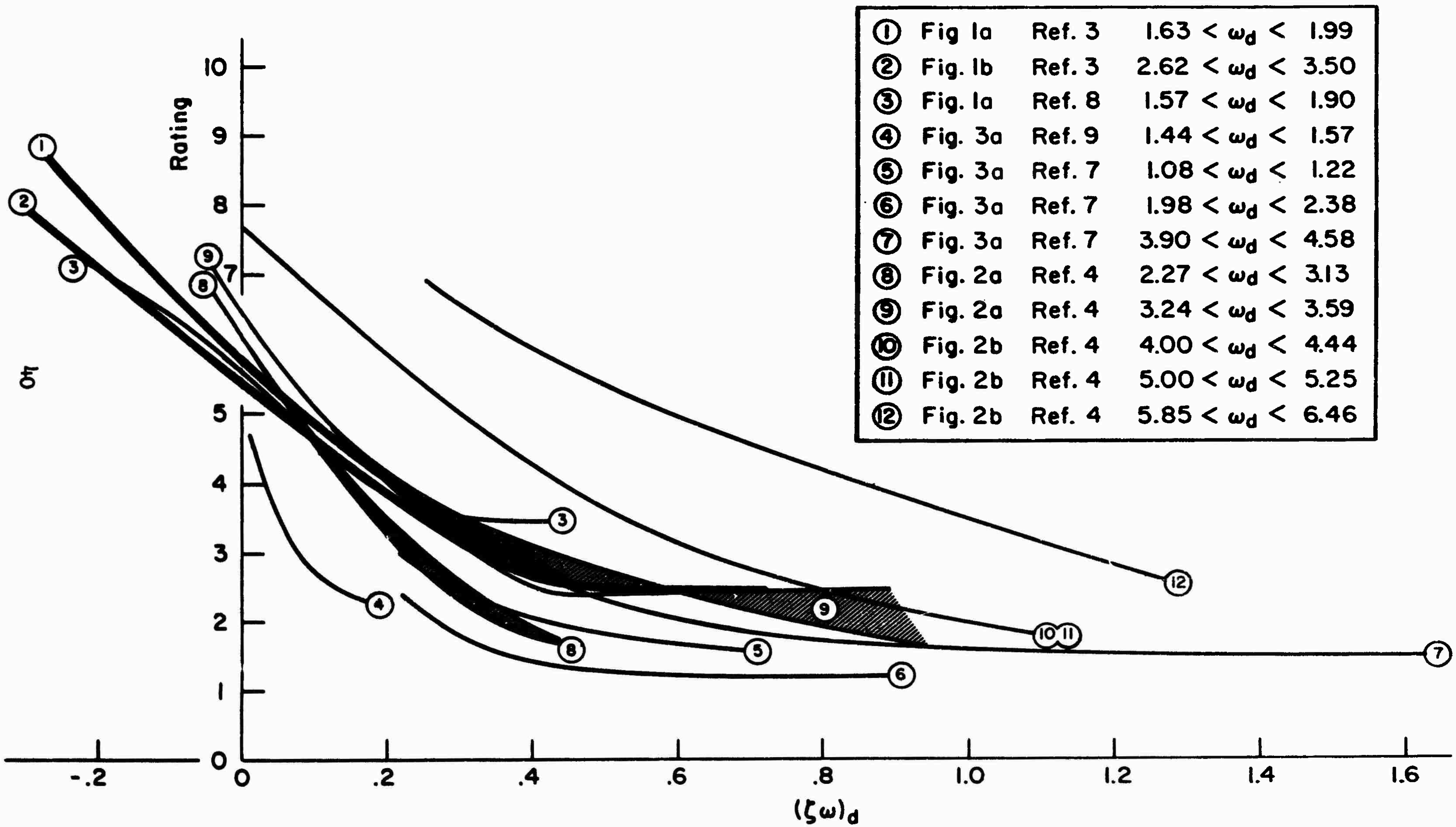


Figure 4. Direct Superposition of All Faired Data
a) Ratings vs. $(\zeta\omega)_d$

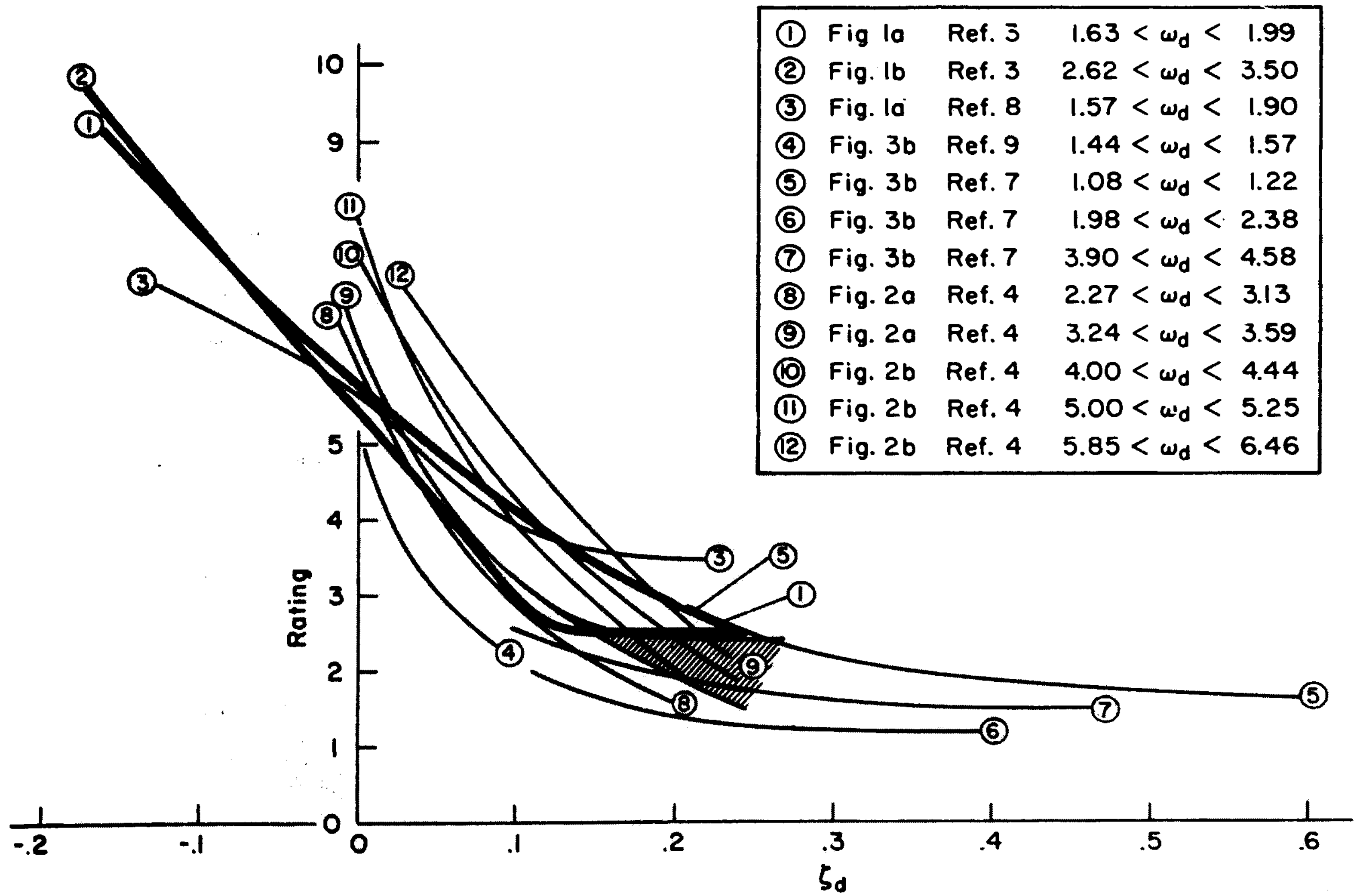
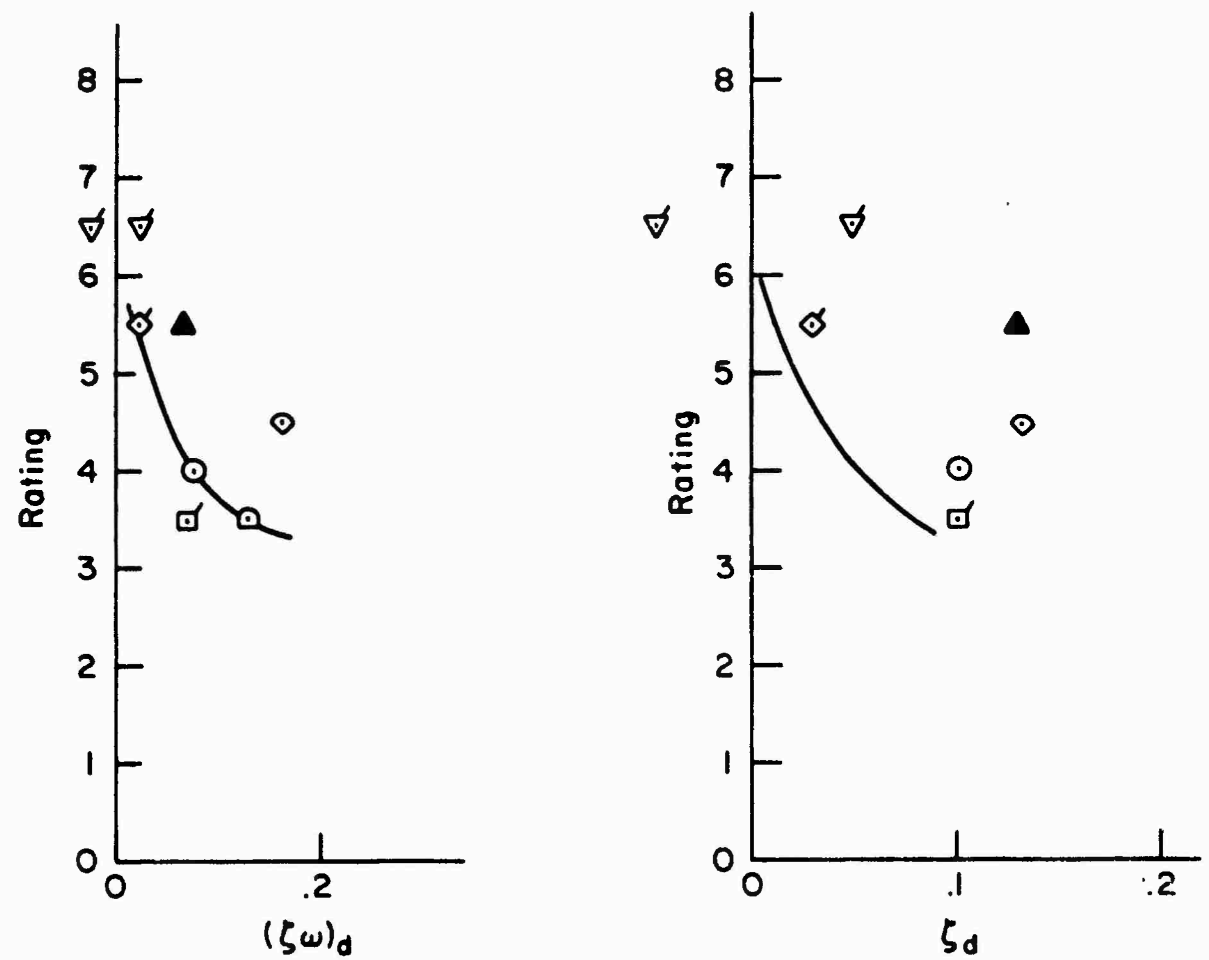


Figure 4 (concl'd). Direct Superposition of All Faired Data
b) Ratings vs. ζ_d



Symbol	Ref	Airplane	ω_d
⊙	14	Brequet 941	.74
▲	12	C-130B	.5
◈	17	RB-52C	.7
⊡	18	C-133B	.7
▽	19	KC-135A	.8
⊡	3	F4D	unrept'd
◇	44	YC-134A	1.16

—— Ref. 9 data (Fig. 3) raised one rating point.

Note: *Filled symbol denotes "abnormal" control problem.*

Flagged symbols denote rating by author on basis of recorded verbal comments.

Figure 5. Collected Low Frequency Data

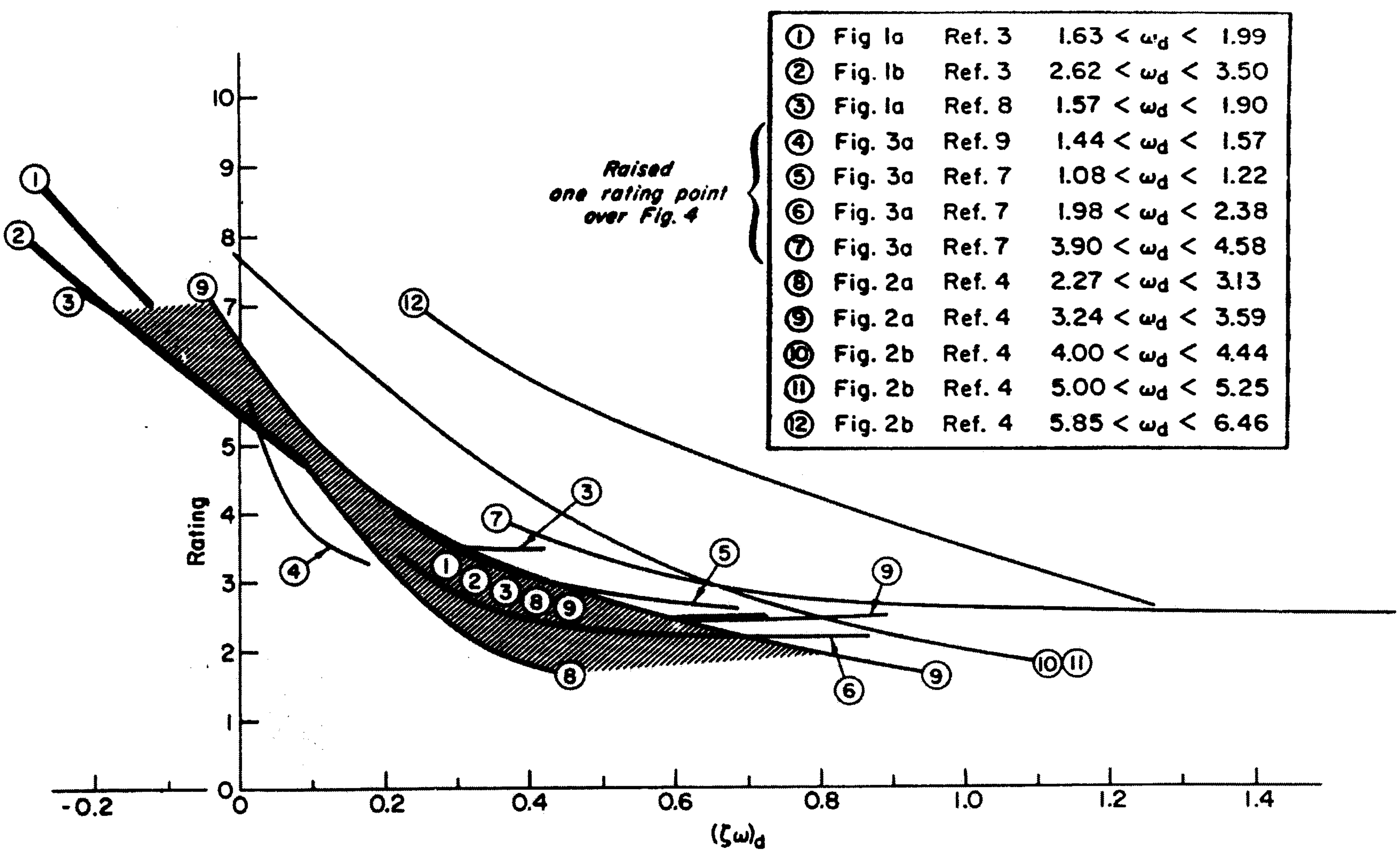


Figure 6 . Superposition of "Adjusted" Faired Data
a) Ratings vs. $(\zeta\omega)_d$

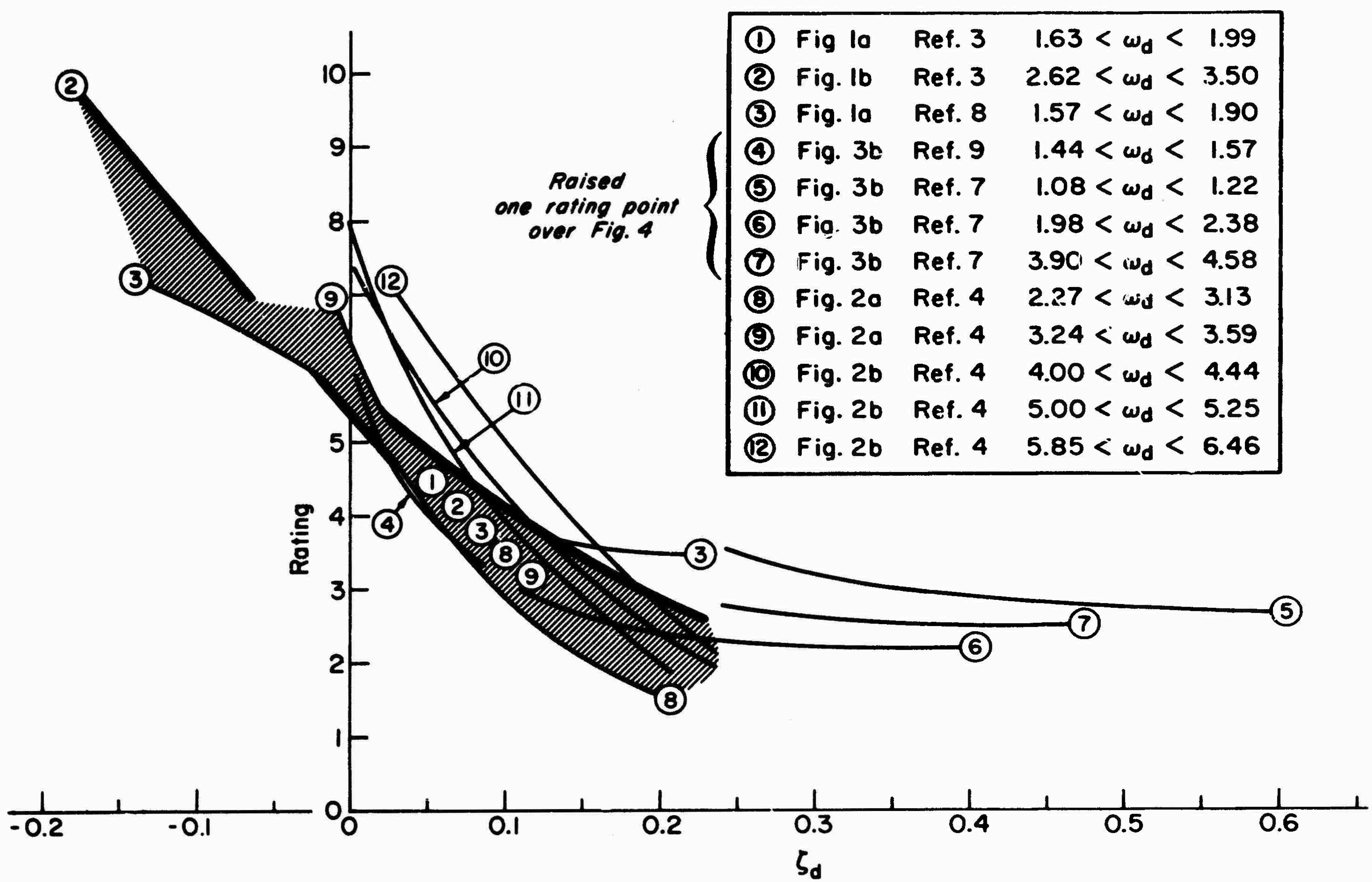


Figure 6 (concl'd). Superposition of "Adjusted" Faired Data
b) Ratings vs. ζ_d

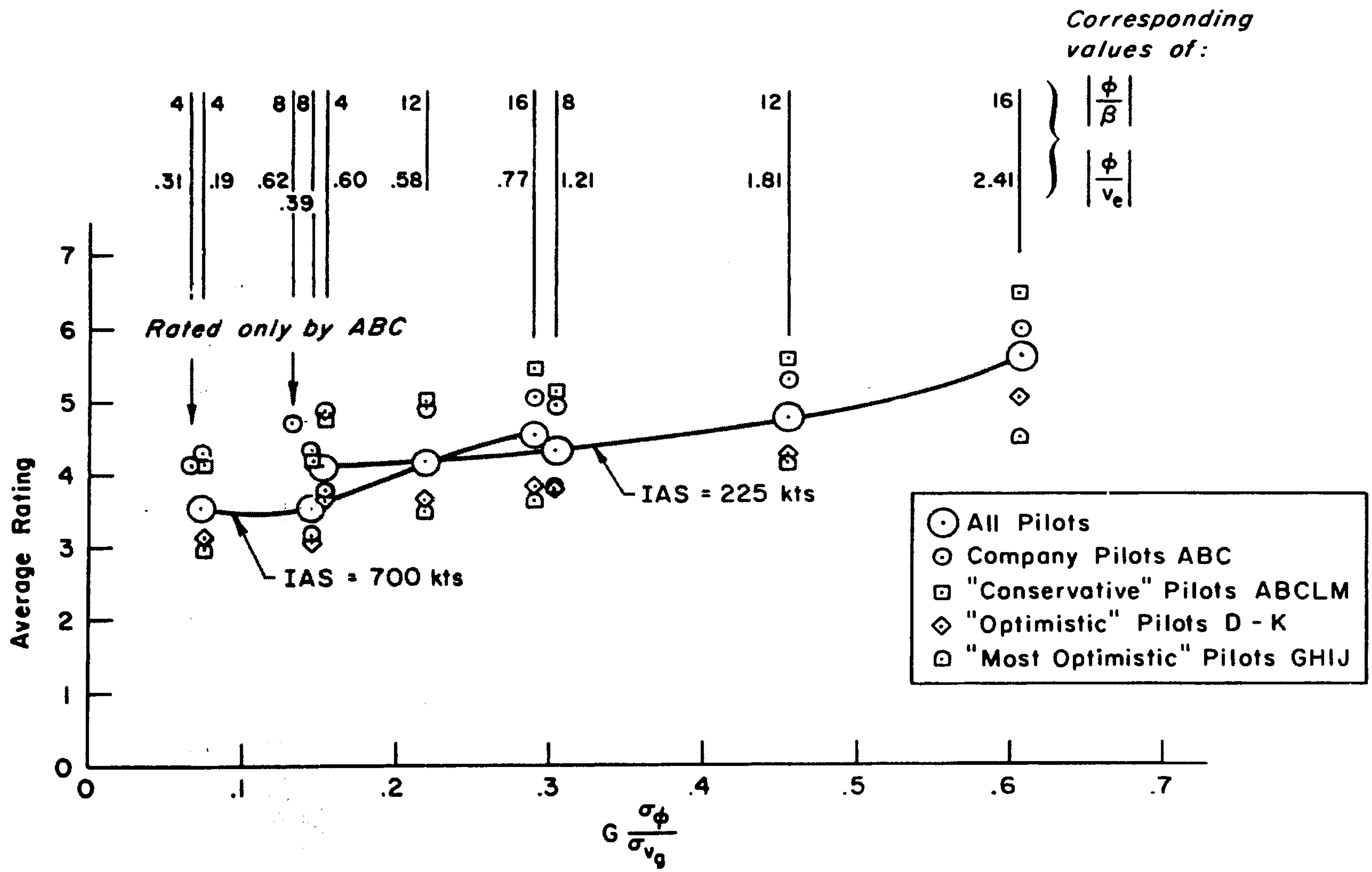


Figure 7. Average Ratings of Ref. 30 – Task II (Heading Change in Rough Air)
a) vs. $G\frac{\sigma_\phi}{\sigma_{v_g}}$

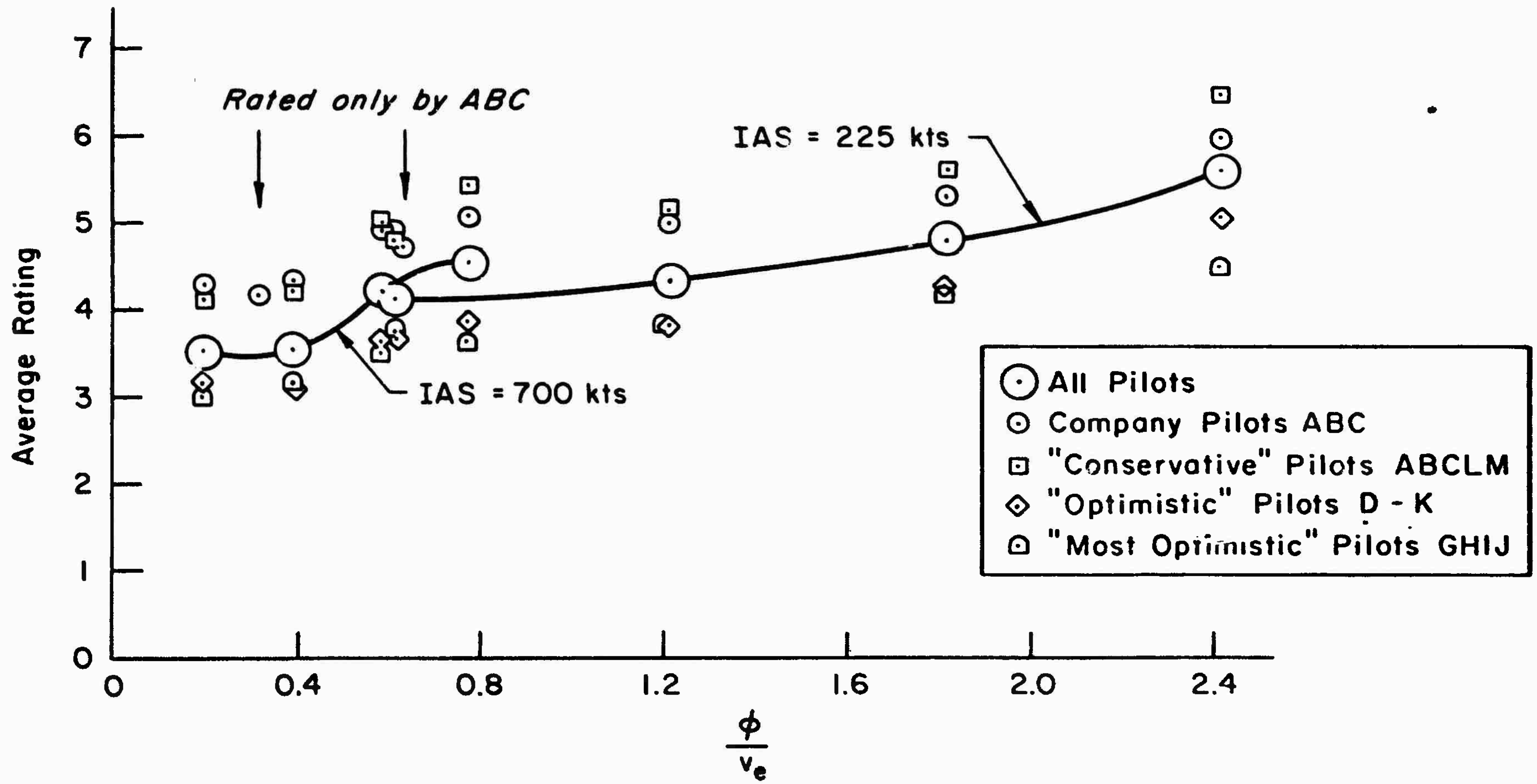


Figure 7 (concl'd). Average Ratings of Ref. 30 — Task II (Heading Change in Rough Air) b) vs. $\left|\frac{\varphi}{v_e}\right|$

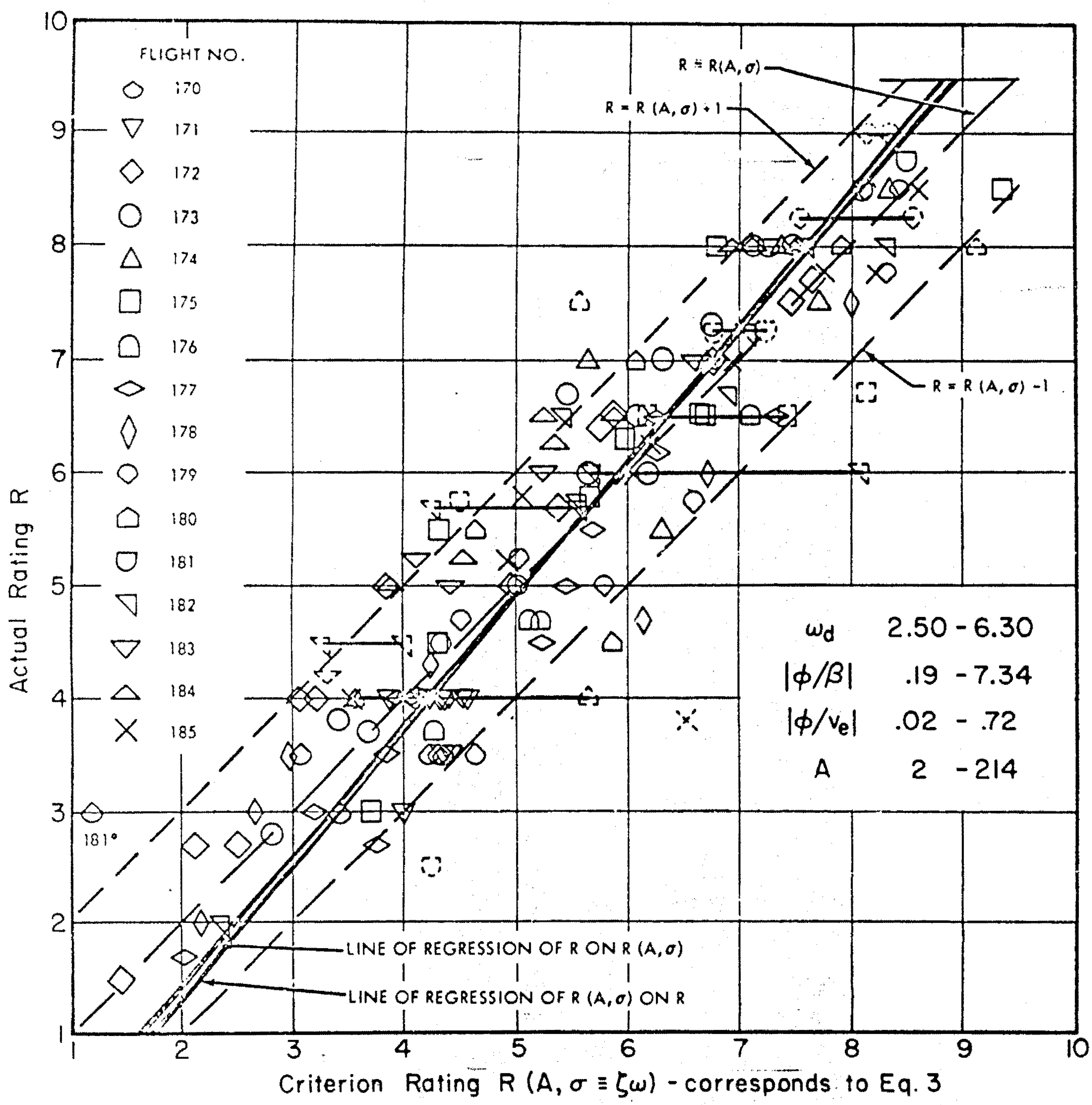


Figure 8. Correlation of the Principal Data (Fig. 6 of Ref. 4) with Eq. 3

Correlation Coefficient = 0.99

Symbol	A, B, C – pilot	⊙	⊡
Ref.	62	66	68
ω_d	1.21 – 2.11	1.98 – 4.58	1.27 – 1.66
$\lvert\phi/\beta\rvert_d$	5.00 – 8.25	4.03 – 9.19	4.69 – 13.5
$\lvert\phi/v_e\rvert_d$	1.00 – 1.65	.55 – 1.24	.88 – 2.52
$\lvert\omega^2\phi/\beta\rvert_d$	11 – 25	22 – 126	10 – 23
$\lvert N'_{\delta_a}/L'_{\delta_a}\rvert$	"Best"	0 – .02	Zero

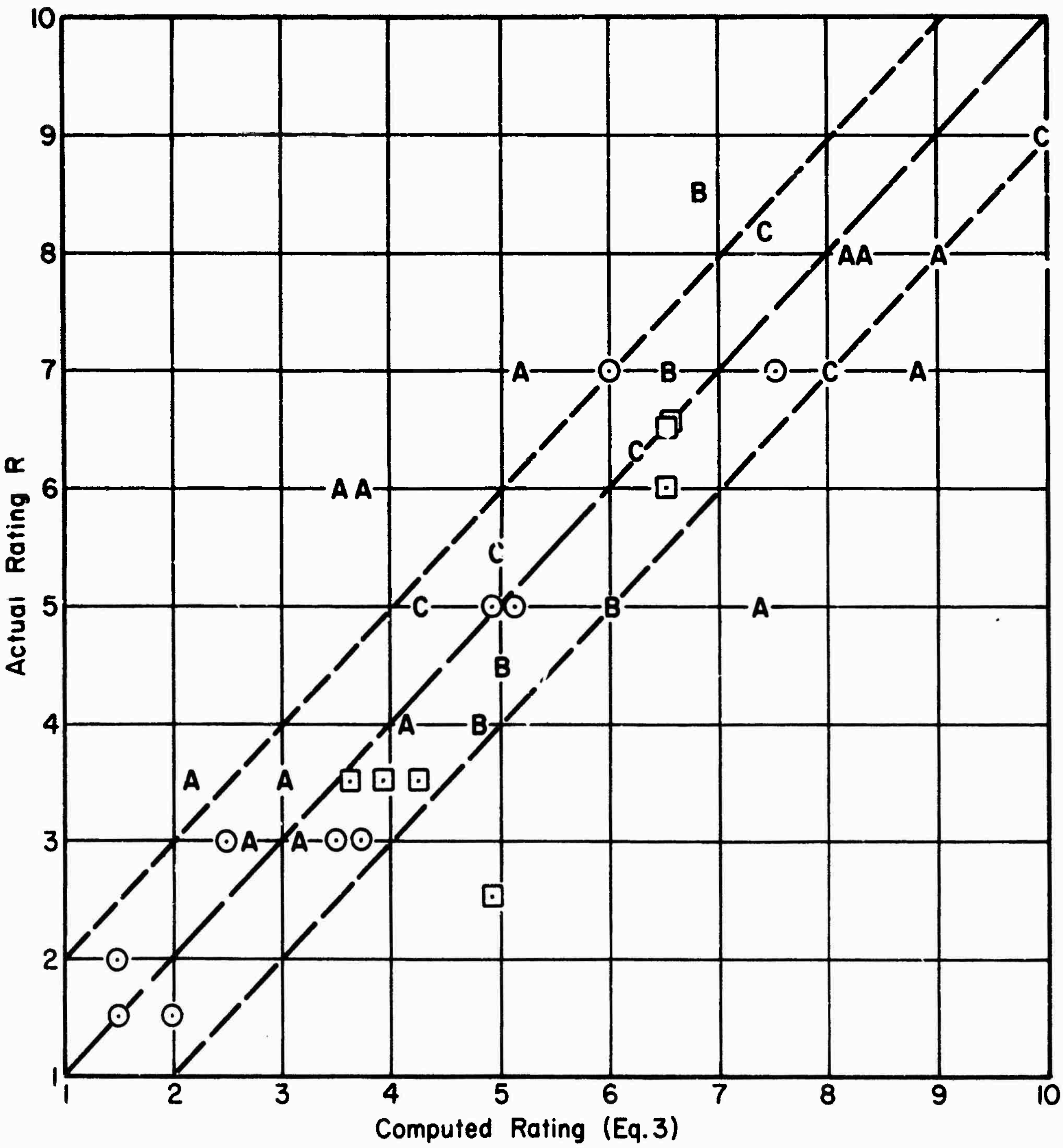


Figure 9. Correlation of Selected Additional Data
a) With Eq. 3

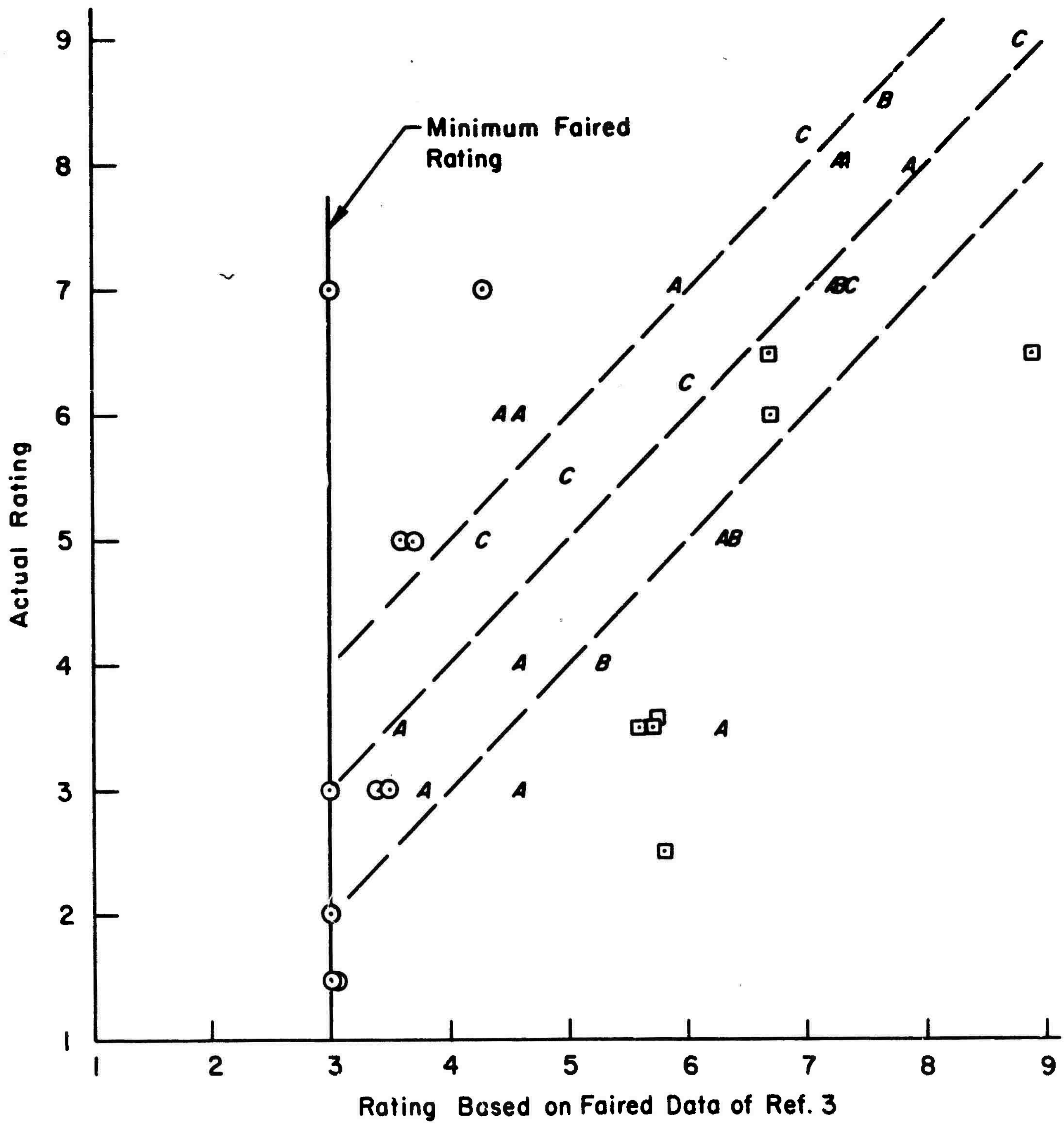


Figure 9 (concl'd). Correlation of Selected Additional Data
b) With Faired Data of Ref. 3 (Fig. 8)

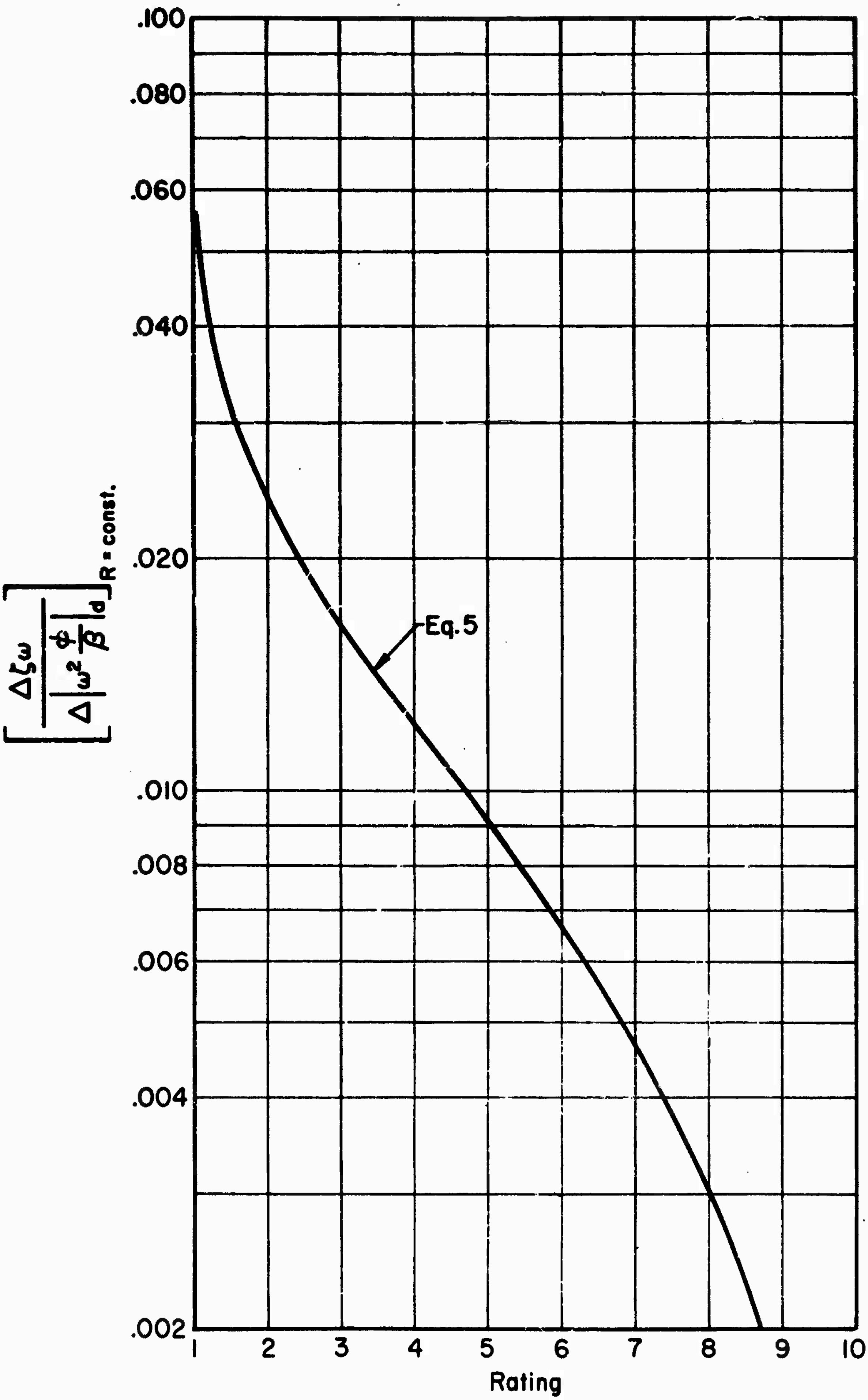


Figure 10. $\frac{\Delta\zeta\omega}{\Delta\left|\omega^2 \frac{\varphi}{\beta}\right|_d}$ Required to Maintain a Given Basic Rating

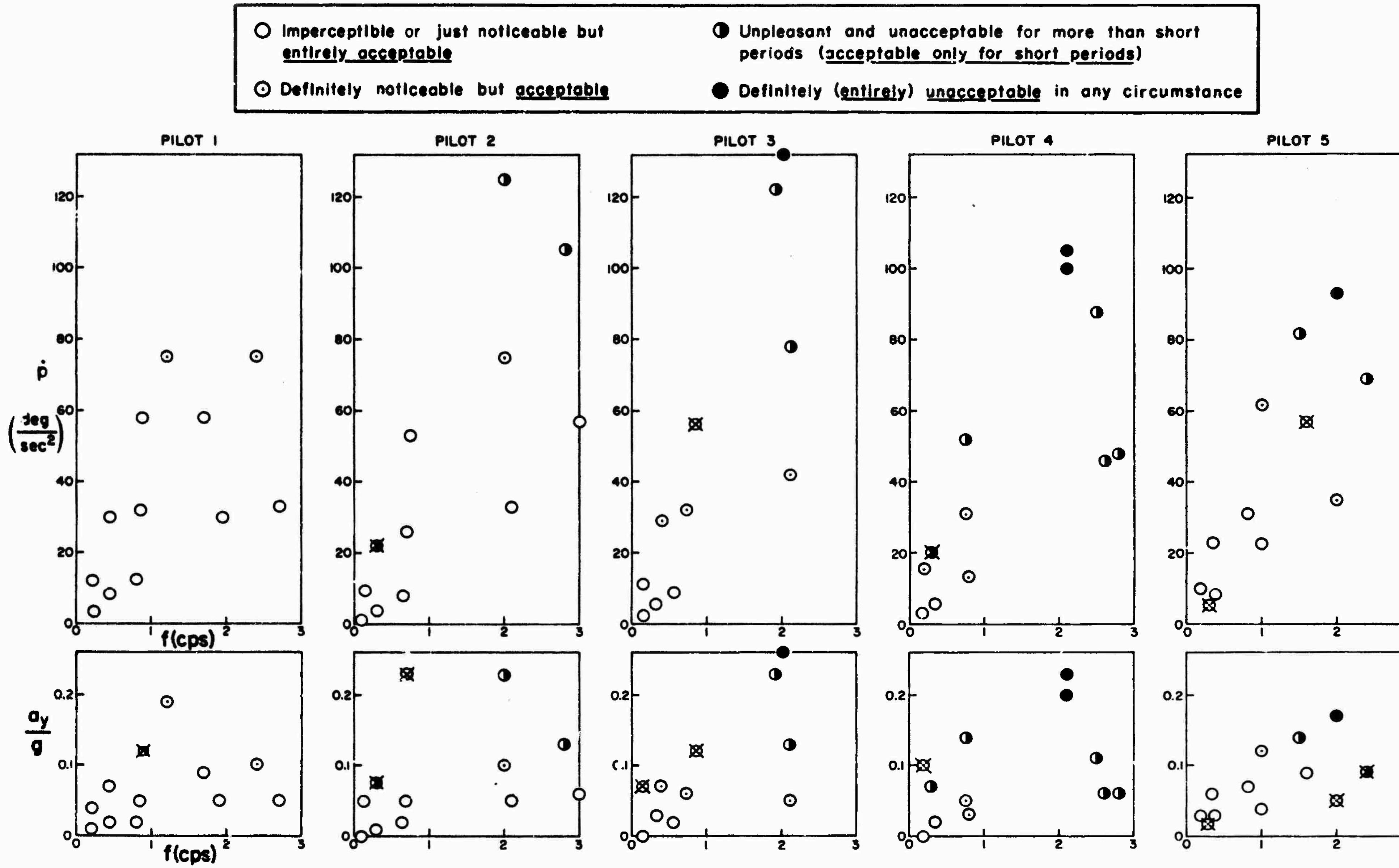


Figure 11. Acceleration Effects on Comfort Rating (From Ref. 32)

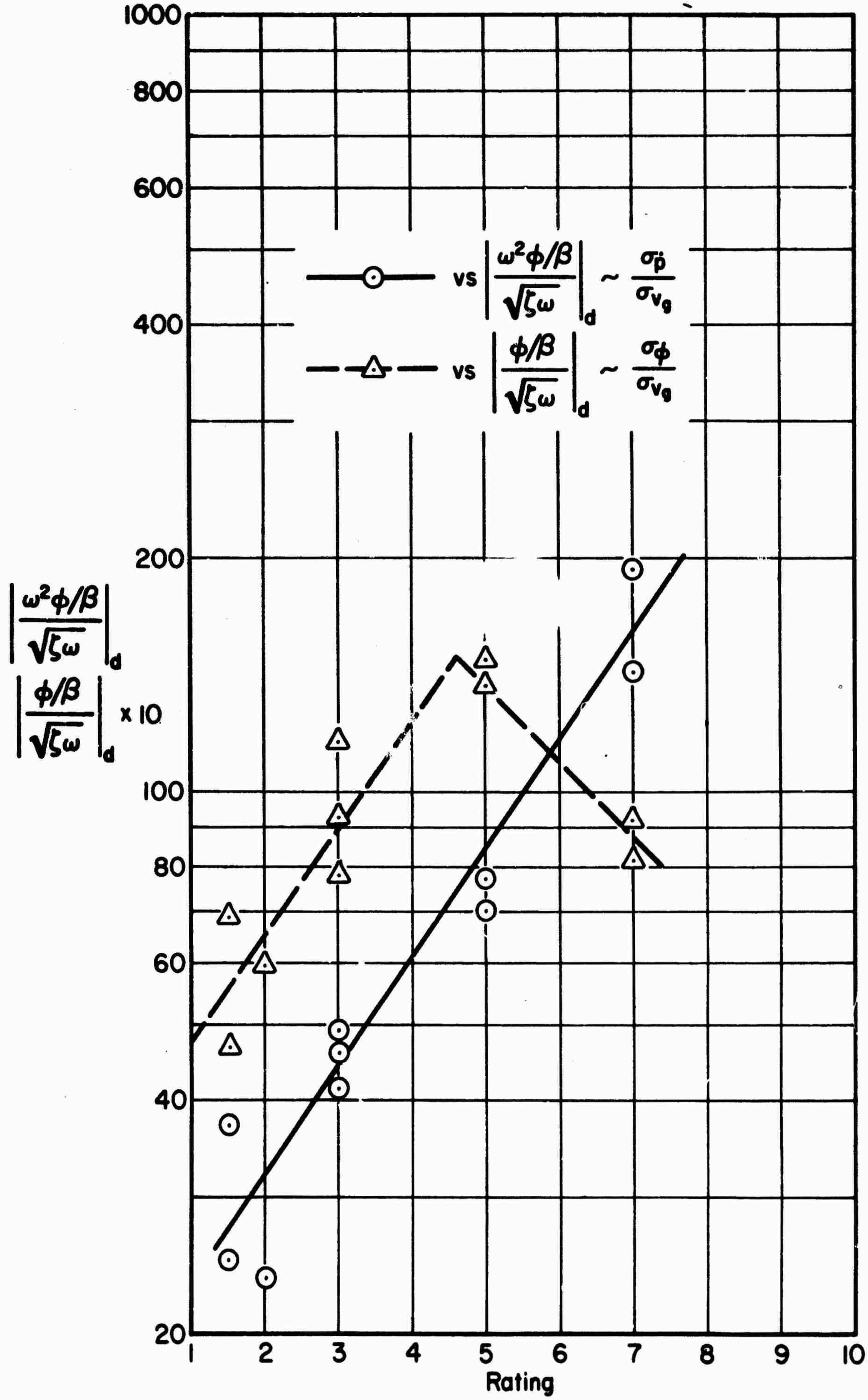
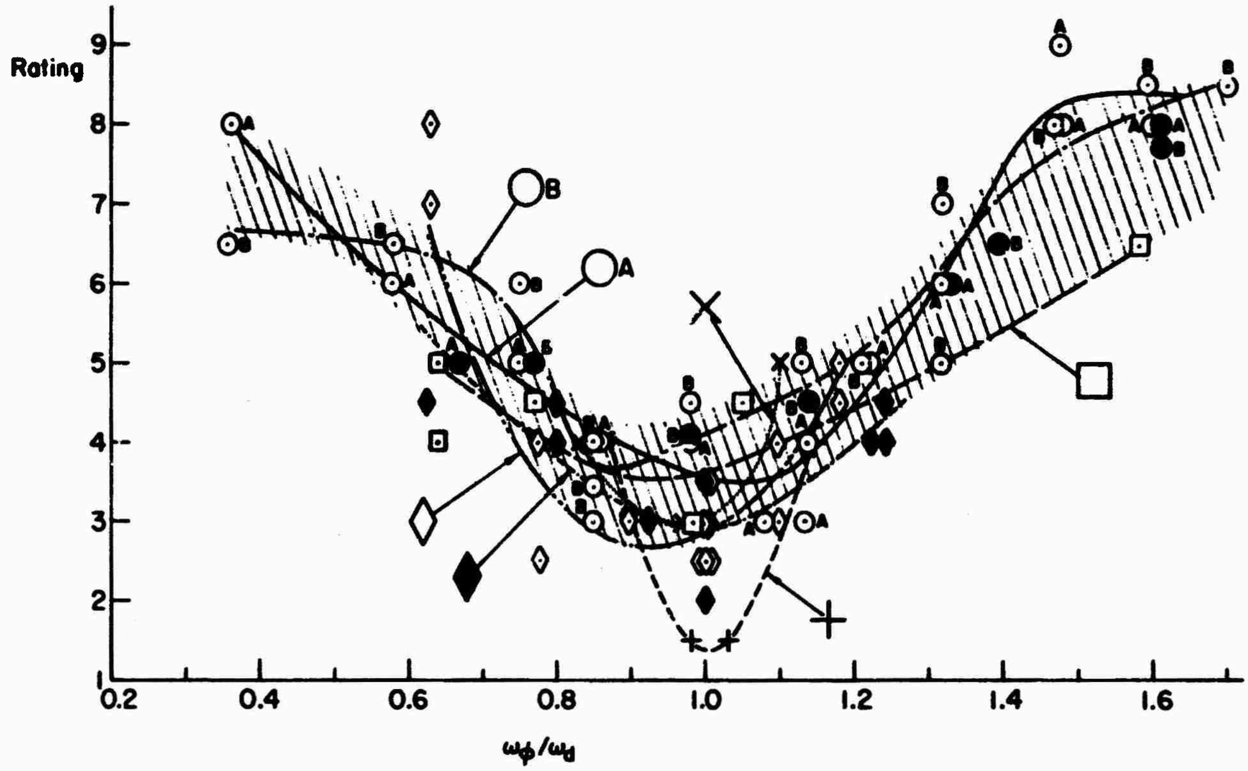


Figure 12. Additional Correlations of Fig. 9, Reference 7 Data



Symbol	Ref.	ζ_d	ω_d	T_R	$\left\lvert\frac{\varphi}{\beta}\right\rvert$	Speed (kt)	Altitude (ft)	Task(s)
⊙ ●	8 (Fig. 6) 8 (Fig. 3)	0.10 0.10	2.00 1.86	0.33	2.1 2.9	170 IAS	10,000	Abrupt $\varphi = 45^\circ - 60^\circ$ turn entries with rudder; abrupt δ_a reversals (δ_r to minimize β) to induce φ oscillations of $\pm 20^\circ$, $\pm 30^\circ$, $\pm 45^\circ$; roll through $\pm 360^\circ$ with and without rudders.
+ ×	7 (Fig. 5) 7 (Fig. 5)	0.12–0.13 0.13–0.17	2.3 2.1–2.4	0.37	2.9–3.5 5.5–7.0	250 IAS	25,000	Straight flight, small turns; $\Delta\psi > 90^\circ$ with $30^\circ < \varphi < 60^\circ$; slow and rapid rolls to $\varphi = 180^\circ$ and 360°; first two plus simulated gusts.
◊ ♦	9 9	0.11–0.13 0.08–0.11	1.5 1.3–1.6	1.5	2.5–5.4 3.0–8.0	185 IAS	5,000	Maneuvers as in Ref. 7 above; rapid turn reversals; 1-min tracking run on a beacon followed by a standard rate turn through $\Delta\psi = 90^\circ$ with roll-out to specific heading.
⊡	34 (Fig. 8)	0.15	1.6	1.4–1.8	6.36	M = 3	70,000	Correction of $\Delta\psi$ initial error followed by on-course straight and level flight holding M and altitude. Maneuvers consistent with passenger transport operation.

Note: Open symbols are fixed-base simulator results, filled symbols (including +, ×) are flight test results; letters designate different pilots.

Figure 13. Rating Correlations with ω_φ/ω_d
a) $\omega_\varphi/\omega_d > .3$ $\zeta_d \doteq .1 - .15$

Ref. 8, $|\phi/\beta|_d \doteq 3$	Ref. 34, $|\phi/\beta| = 6.36$
$T_R = .33$, $1.6 < \omega_d < 1.9$	$\omega_d \doteq 1.6$
◺ $\zeta = -.13$	
△ $\zeta = -.06$	
◇ $\zeta = .01$	◇ $\zeta = .06$, $T_R = 4.7$
⊡ $\zeta = .10$	⊡ $\zeta = .15$, $T_R = 1.8$
⊙ $\zeta = .22$	⊙ $\zeta = .22$, $T_R = 1.4$

Note: Open symbols are fixed base simulator results
Closed symbols are flight test results (Pilot A where not indicated)

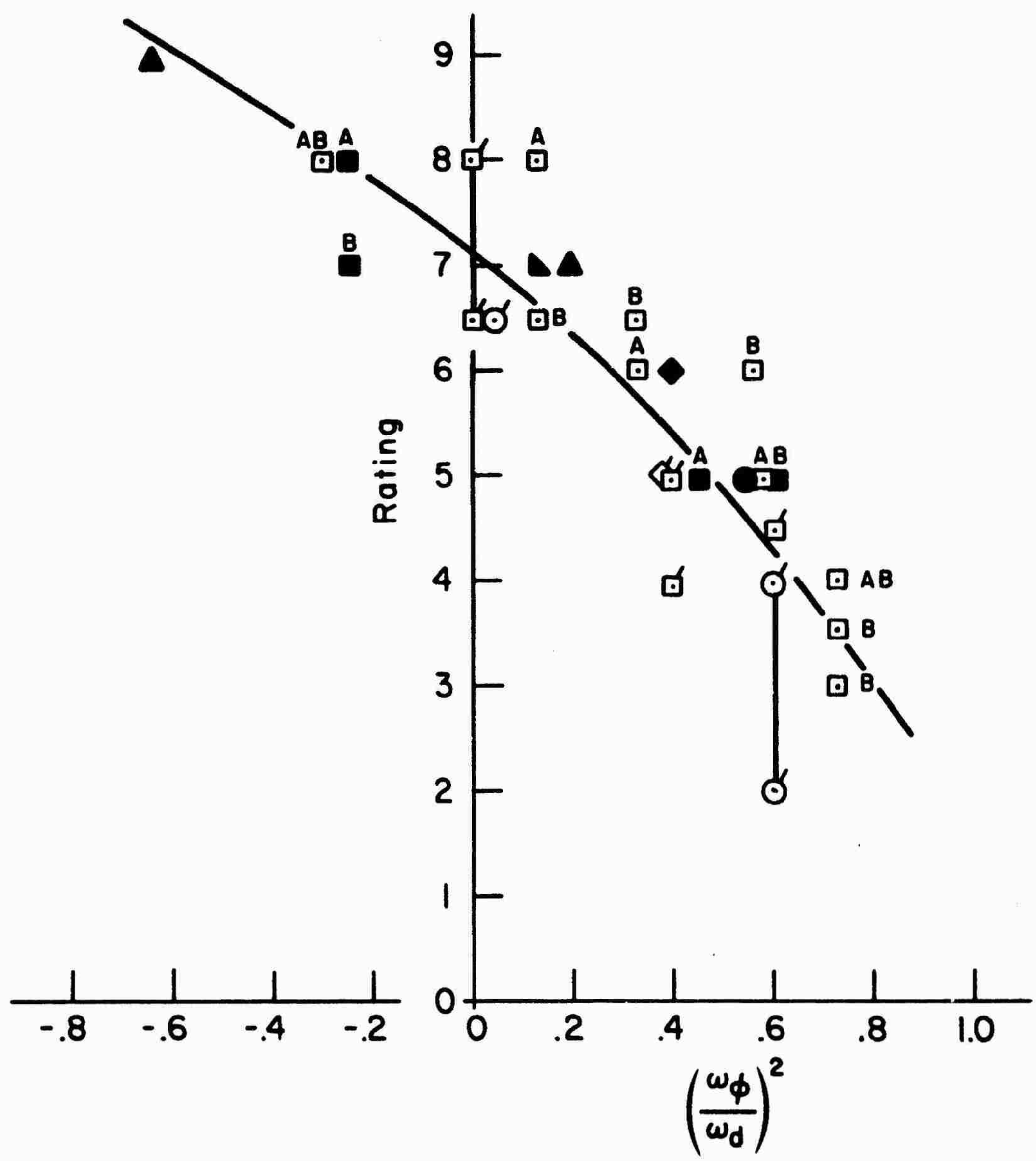


Figure 13 (concl'd). Rating Correlations with ω_ϕ/ω_d
b) $(\omega_\phi/\omega_d)^2 < .7$

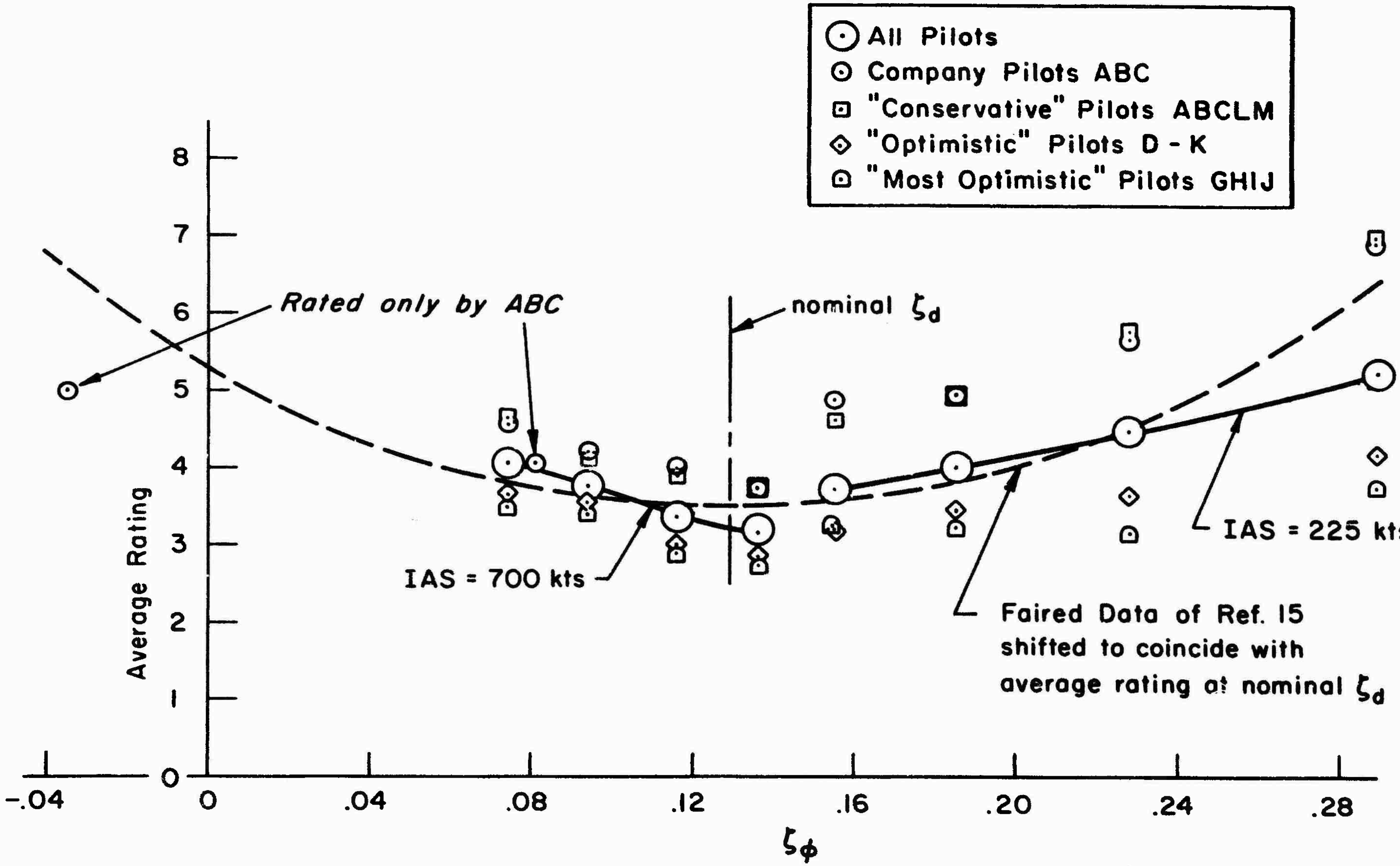


Figure 14. Average Ratings of Ref. 30 – Task III (360° - 1g Roll)
a) vs. ζ_φ

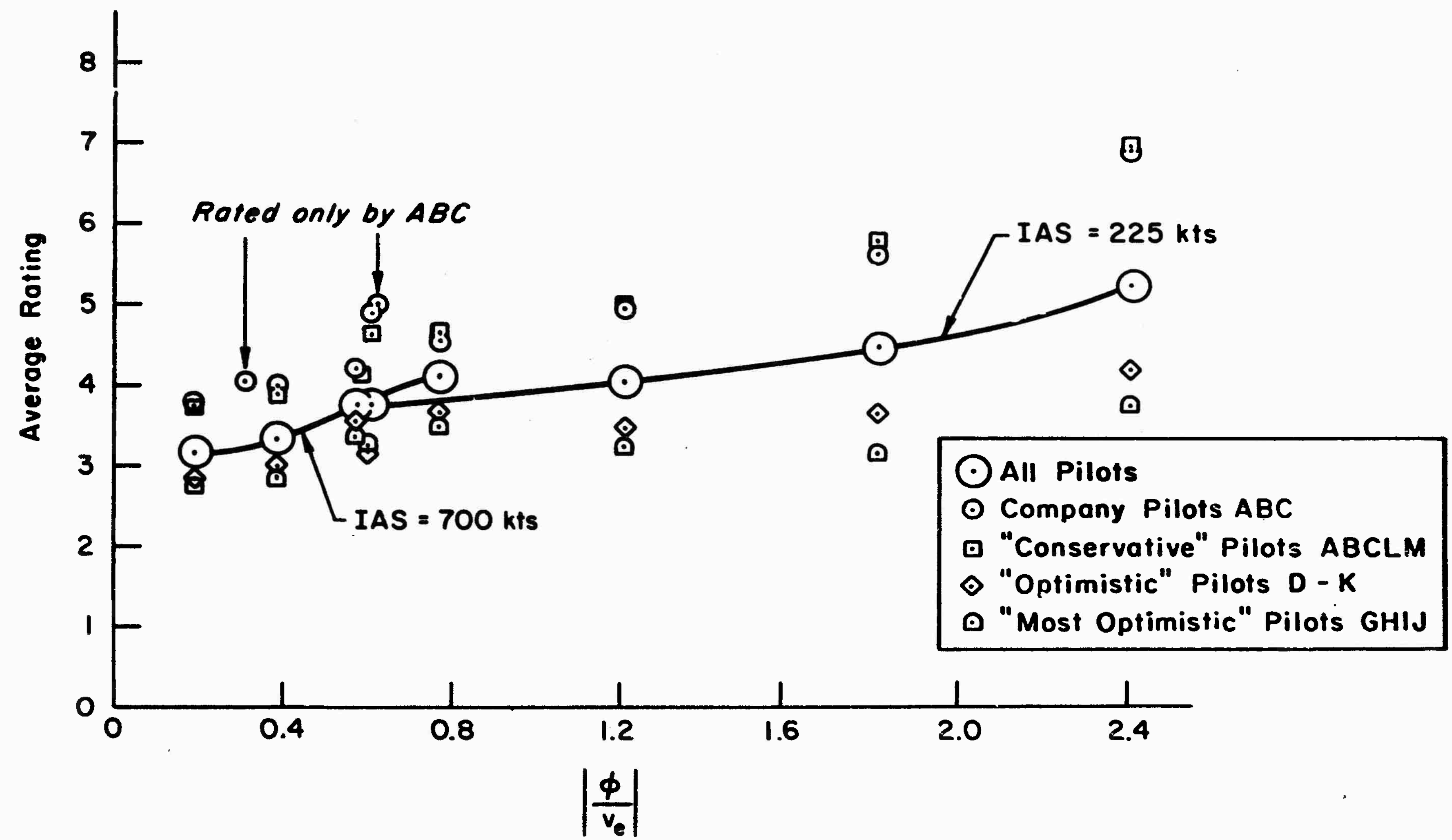


Figure 14 (concl'd). Average Ratings of Ref. 30 – Task III (360° - 1g Roll)
b) vs. $\frac{\varphi}{v_e}$

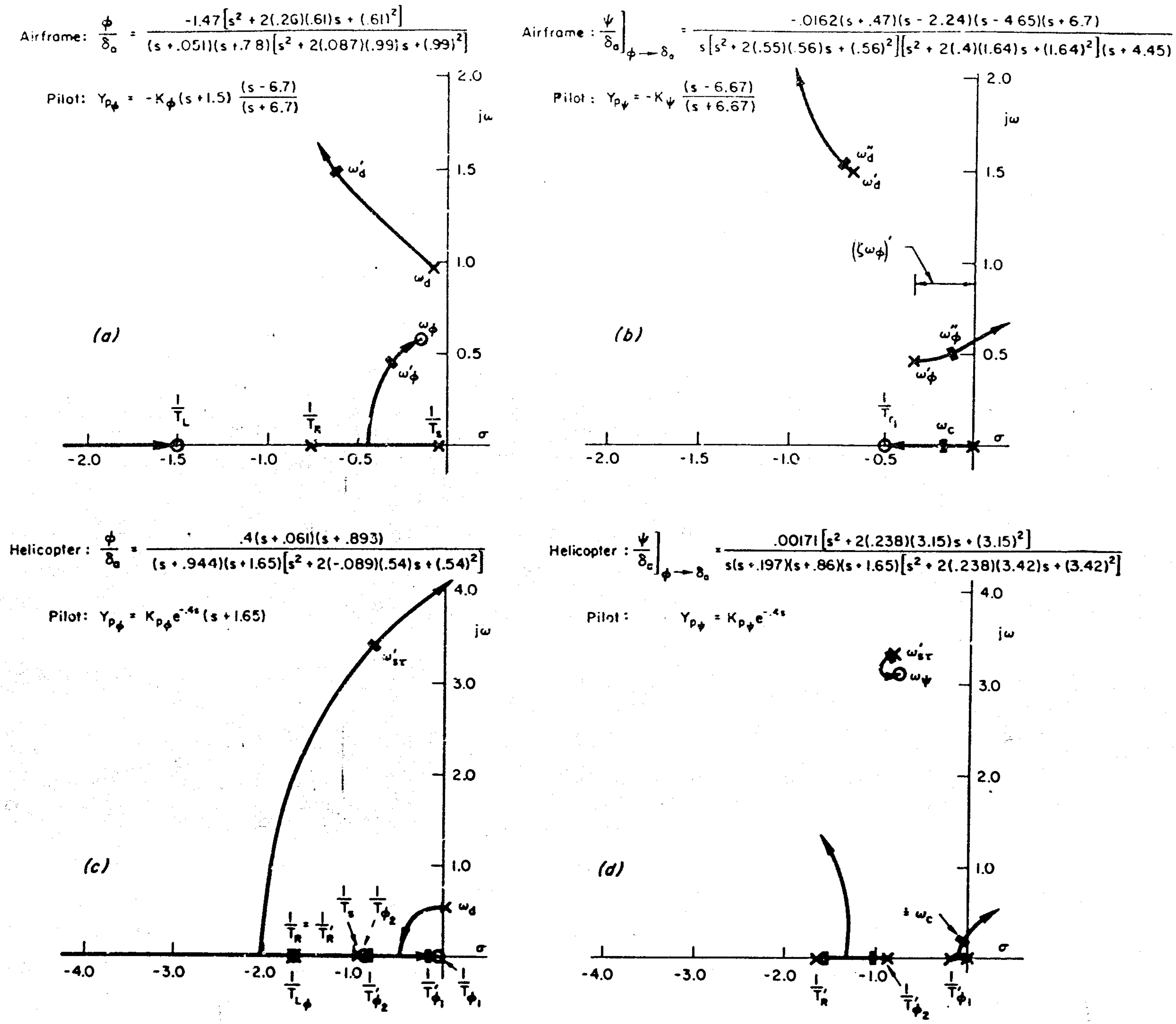


Figure 15. Closed-Loop Aspects of Heading Control (from Refs. 75 and 95)

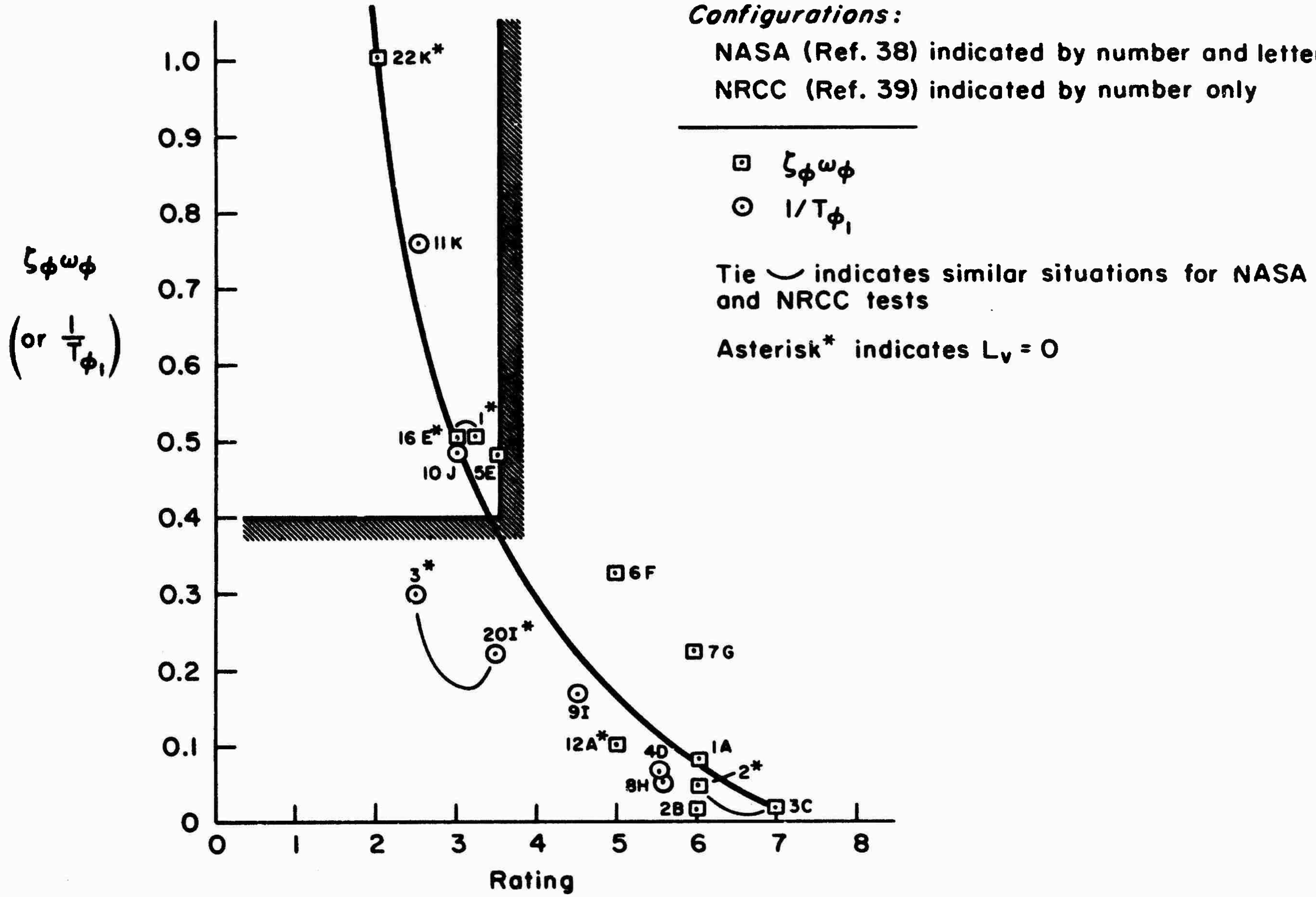


Figure 16. Heading Control Ratings vs. $\zeta_\varphi \omega_\varphi$ (or $1/T_{\varphi_1}$)

APPENDIX

COMMENTS RECEIVED ON DRAFT VERSION OF REPORT
(STI Working Paper 133-2)

T. Collins, J. Walker, General Dynamics/Fort Worth........Verbal 7/24/64

Feel that at high speed roll angle doesn't bother pilot because airplane "just bores on."

A. G. Barnes, British Aircraft Corporation Limited........Letter 8/26/64

1. Have evidence of inconsistencies in conventional Dutch roll criteria (ζ_d, φ/β, ω_φ/ω_d).

2. Would modify tentative conclusion to read "Pilot ratings are related to $\zeta\omega$ rather than ζ for all ω_d greater than (say) 1.0 rad/sec."

3. For low ω_d, especially worried about cases dismissed as secondary in which ($N_p' - g/U_o$) and I_{xz} are dominant.

4. $|\omega^2(\varphi/\beta)|$ looks promising since it may be applicable to all configurations, flight conditions, and sizes of aircraft.

5. Hard to believe that pilot rating relationship with $\zeta\omega$ holds when ω is high, e.g., 6 rad/sec; however, may not be important because knows of no aircraft which would have such characteristics.

6. Raising the Ref. 9 data by one point on the basis of Fig. 5 arguable because of factor of two on ω_d between Ref. 9 and remaining data.

7. Their simulation/flight-test correlation is better than indicated on page 21 (of WP-133-2); even so, has strong reservations about possibility of using fixed-base simulation to explore all ω_φ/ω_d effects, particularly for high L_β' or for "violent" maneuvers.

A. G. Barnes, British Aircraft Corporation Limited.......Verbal 9/25/64

8. The data used (Item 7 above) are no good because of fixed-base roll display servo lags — see Ref. 10.

9. Concerned with pilot location effects on a_{y_p}.

10. Pilot can't fly $N_\beta \rightarrow 0$ even though N'_β is finite at high speed, but on approach can manage $N_\beta \rightarrow 0$. Says (RAE TN Aero 2921) shows $\zeta = 0$ is O.K. on approach if

    a. Have lots of control

    b. Can control with ailerons only, therefore don't mind low ζ

R. A'Harrah, North American Aviation—Columbus............Verbal 9/15/64

Questions the use or importance of $\dot{p}$ as contrasted to a_y.

W. B. Kemp, Jr., M. T. Moul, A. A. Schy, NASA-LRC........Letter 9/18/64

1. Question $\zeta\omega$ for high ω. Not supported by Ref. 11.
2. ω effect does come in through $\omega^2(\varphi/\beta)$; therefore, conclusion in last paragraph on page 15 (of WP-133-2) is misleading.
3. Confusion on different "A" parameters; however, share the opinion that φ/v_e no good at high altitude.
4. Conclusion that φ/β effects can't be evaluated in fixed-base simulator not justified from discussion, i.e., no evidence to support claim that pilot is not concerned with $\dot{p}$.

J. Weil, L. Taylor, NASA-FRC............................Verbal 10/1/64

1. $\zeta\omega$ no good as $N_\beta \rightarrow 0$; O.K. for $\omega_\varphi^2 > 0$, no good for $\omega_\varphi^2 < 0$.
2. a_y versus $\dot{p}$? $\dot{p}$ important in roll; a_y can feed pilot-induced oscillation.
3. Feel that φ/β effects can be simulated fixed-base; think $\dot{p}$ is secondary.

H. C. Higgins and others, The Boeing Company............Letter 10/5/64

1. The data do not always clearly support the conclusions.

2. "Ideal" lateral-directional characteristics should include

   a. Possibility of two-control turn with $\beta = 0$ <u>or</u> (β) programmed with φ to minimum a_y at pilots' or passenger station.

   b. "Tuned" lateral-directional gust response so that best compromise selected between gust-induced acceleration, attitude, and flight path disturbances.

3. Argument versus fixed-base-evaluated $\omega^2(\varphi/\beta)$ effects not completely convincing, i.e., highly experienced pilot <u>could</u> watch $\dot{p}$.

4. Pilot location effects, i.e., a_{y_p}, <u>may</u> strongly influence φ/β, ω_φ/ω_d effects.

5. Correlations with $\zeta\omega$ rather than ζ only slightly better; however, agree that ζ not sufficient to describe acceptable dynamics.

6. Requirements format based on minimum ζ in absence of cross-coupling plus additional requirements for coupling seems logical.

7. May be an increase in required damping at <u>high</u> ω_d due to yawing accelerations (as well as rolling). Flight experience in light planes (e.g., Bonanza) with low φ/β and <u>low</u> damping suggest this.

Mel Sadoff, NASA-ARC...Verbal

ω_φ/ω_d effects of Ref. 34 roughly consistent with those of Ref. 8.

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Part I: Roll Handling Qualities
Part II: Lateral-Directional Oscillatory Handling Qualities

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13. ABSTRACT This report is a codification in two parts of conventional aircraft handling qualities criteria. The results of this effort are to serve as an intermediate design guide in the areas of lateral-directional oscillatory and roll control. All available data applicable to these problem areas were considered in developing the recommended new criteria. Working papers were sent to knowledgeable individuals in industry and research agencies for comments and suggestions, and these were incorporated in the final version of this report. The roll handling qualities portion of this report uses as a point of departure the concept that control of bank angle is the primary piloting task in maintaining or changing heading. Regulation of the bank angle to maintain heading is a closed-loop tracking task in which the pilot applies aileron control as a function of observed bank angle error. For large heading changes, the steady-state bank angle consistent with available or desired load factor is attained in an open-loop fashion; it is then regulated in a closed-loop fashion throughout the remainder of the turn. For the transient entry and exit from the turn, the pilot is not concerned with bank angle per se, but rather with attaining a mentally commanded bank angle with tolerable accuracy in a reasonable time, and with an easily learned and comfortable program of aileron movements. In the lateral oscillatory portion of this effort, in defining requirements for satisfactory Dutch roll characteristics, a fundamental consideration is the fact that the motions characterizing this mode are ordinarily not the pilot's chief objective. That is, he is not deliberately inducing Dutch roll motions in the sense that he induces rolling and longitudinal short-period motions.

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13. (Continued) Dutch roll oscillations are side products of his attempts to control the airplane in some other mode of response, and they are in the nature of nuisance effects which should be reduced to an acceptable level. In spite of its distinction as a side effect, adequate control of Dutch roll is a persistent handling qualities research area and a difficult practical design requirement. The difficulties stem from the many maneuver and control situations which can excite the Dutch roll, and from its inherently low damping. Since any excitation of the Dutch roll is undesirable, the effects of disturbance inputs are almost uniformly degrading to pilot opinion rating. Nevertheless, removal of such influence does not eliminate the need for some basic level of damping. A worthwhile approach to establishment of Dutch roll damping requirements is to first establish the basic level, and then to study the varied influences of the disturbance parameters. This approach provides the basis for the material contained in this report.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Handling Qualities Lateral-directional Handling Qualities Roll Handling Qualities Handling Qualities Requirements Airplane Handling Qualities						

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